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Cage and pen fish farming

Carrying capacity models and environmental impact

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by
Malcolm C.M. Beveridge
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Rome, 1984

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M-40
ISBN 92-5-102163-5

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PREPARATION OF THIS DOCUMENT

In 1956 the Food and Agriculture Organization established a Programme of André Mayer Research Fellowships in memory of an outstanding scientist and humanitarian who was very active in the formation and early history of the Organization. The Programme provides a number of fellowships in each biennium to young scientists to carry out specific research tasks for the Organization. In 1982, Mr. Malcolm Beveridge was awarded an André Mayer Fellowship to carry out "Cage culture research with special emphasis on techniques employed for estimating the carrying capacity of the water bodies used". Mr. Beveridge, who had already carried out research on the environmental impacts of cage culture on some Scottish lakes, spent ten months in the Philippines, working in collaboration with the University of the Philippines, studying environmental factors related to cage culture under tropical conditions. This Technical Paper is a report of his findings.

Mr. Beveridge has returned to the Institute of Aquaculture, Stirling University, where he is teaching and carrying on research in various aspects of aquaculture. The Organization is grateful to both the University of Stirling and the Overseas Development Administration of the United Kingdom who also helped support this project.

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For bibliographic purposes this document should be cited as follows:

Beveridge, M.C.M., 1984 Cage and pen fish farming. Carrying capacity models and environmental impact. FAO Fish.Tech.Pap., (255):131 p.

ACKNOWLEDGEMENTS

I wish to thank the following people and organisations who helped by providing advice and information during the compilation of this report

- The Staff at the Institute of Fisheries Development and Research and the College of Fisheries, University of the Philippines, particularly the Director of IFDR Dr. Florian Orejana, Professor Tony Mines and Dr. Gaudiosa Almazan

- The GTZ group, College of Fisheries, University of the Philippines

- The Director and Staff of SEAFDEC, Binangonan Station, Rizal, Philippines

- The Director and Staff of ICLARM, Manila, Philippines

- Dr. R.D. Guerrero III, Technical Resources Centre, Manila, Philippines

- Dr. L. Oliva, University of Southern Mindanao, Philippines

- Mr. Ben Raneses, St. Peter's Fish Farm, Pillila, Rizal, Philippines

- Mr. Job Bisuna, Jobski Fish Farms, Baao, Camarines Sur Philippines

- Professor S. Mori, Kyoto, Japan

- Dr. Y. Kitabatake, Japan Environment Agency, Japan

- Dr. J. Thornton, National Institute for Water Research, Pretoria

- Dr. Z. Fischer, Director, Instytut Ekologii Pan, Poland

- Professor Jager, Inst. fur Meereskunde, Kiel, W. Germany

- Dr. J. Clasen, Sieburg, W. Germany

- The Director and Staff of the Institute of Aquaculture, University of Stirling, particularly Dr. J.F. Muir, Dr. M. Phillips, Mr. A. Stewart, Dr. K. Jauncey, Dr. C. Sommerville and Dr. L. Ross

I would also like to thank ODA, particularly Mr. J. Stoneman (Fisheries) and Mr. A. Armstrong (U.N. Desk) for assistance during the course of my work, and Mr. A. Kyle, British Council, Manila, for help with communications.

I would also like to express my gratitude to the Director and Staff of FAO in Manila, and the Director and Staff of FIRI, FAO, Rome, for all their help.

Finally, I would like to thank Mrs. Moira Stewart, Institute of Aquaculture, Stirling, for typing this report.

ABSTRACT

The use of cages and pens to rear fish in inland waters is an increasingly popular method of fish culture, involving relatively low initial costs, and simple technology and management methods. However, these water-based culture methods differ from land-based operations such as ponds and raceways in that they are open systems, where interaction between the fish culture unit and the immediate environment can take place with few restrictions, and they are often sited in publicly-owned multi-purpose water bodies. Thus any impacts may lead to a conflict of interests.

A number of studies have demonstrated that the cage and pen structures can affect the multi-purpose nature of water bodies, by restricting space which might otherwise be used for fisheries, recreation or navigation, and by interfering with currents and sediment transport. In some circumstances predators and disease-bearing organisms have been introduced or attracted to the site. However, the most significant impacts are due to the method of culture employed.

Intensive operations can affect water quality, and influence the biomass and diversity of the benthos, plankton and nekton. It is argued that the P loadings to the environment are the most important components of the wastes. The role of P in the diets of fishes is reviewed, total-P loadings are quantified for both intensive tilapia and trout culture operations, and the P loading models developed by Dillon and Rigler (1974) adapted to predict the environmental impact of intensive cage culture on the aquatic environment. Tentative development limits are also proposed.

Following a review of current information on energy transfer from plant to herbivorous fish in ponds and lakes, efficiencies of 1.0 - 3.5% plant carbon : fish carbon are suggested as attainable from extensive cage or pen culture. This is considerably higher than yields from lentic bodies managed for fisheries. The efficiency of transfer will vary with productivity, and the relationship between primary production and fish yield is likely to be sigmoid, as suggested by Liang et al (1981) for fisheries yields.

The carrying capacity of freshwaters for semi-intensive culture depends upon the quality and quantity of feed used, and the productivity of the site. A simple model, combining extensive and intensive-type models is proposed.

The models proposed for use in predicting the environmental impact of cage and pen culture are in the initial stages of development and have yet to be validated and calibrated. Several methods for reducing the impact of intensive culture methods are proposed, and these include combining with extensive operations. Finally, it is proposed that some categories of water body may be unsuitable for large scale culture operations.

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Chapter 1

GENERAL CONSIDERATIONS

1.1 INTRODUCTION

The purpose of this report is to review what is known about the environmental impact of inland water cage and pen fish culture, and to examine possible methods for estimating carrying capacity. Efforts have been made to deal not only with intensive culture in temperate countries, but also with the more extensive methods practiced in the tropics, and to choose predictive models which are comparatively simple and inexpensive to use.

The report proper is preceeded by a brief account of cage and pen culture, and its relative importance in contemporary aquaculture.

1.2 CAGE AND PEN CULTURE AND ITS HISTORY

There is some confusion concerning the terms 'cage culture' and 'pen culture' in fish farming. Both terms are often used interchangeably, particularly in North America, where 'sea pens' and 'sea cages' describe the same method of culture (e.g. Novotny, 1975, Saxton *et al*, 1983), or the general term 'enclosure culture' is used to describe what more precisely could be defined as cage or pen culture (e.g. Milne, 1979). Both cage and pen culture are types of enclosure culture, and involve holding organisms captive within an enclosed space whilst maintaining a free exchange of water. The two methods, however, are distinct from one another. A cage is totally enclosed on all, or all but the top, sides by mesh or netting, whereas in pen culture the bottom of the enclosure is formed by the lake or sea bottom (Fig. 1).

Like most other types of aquaculture, cage culture began in Southeast Asia, although it is thought to be of comparatively recent origin (Ling, 1977). It seems to have developed independently in at least two countries. According to Pantalu (1979), the oldest records of cage culture come from Kampuchea where fishermen in and around the Great Lake region would keep *Clarias* spp. catfishes and other commercial fishes in bamboo or rattan cages and baskets until ready to transport to market. In captivity, the fishes were fed kitchen scraps and were found to grow readily. This traditional method of culture has been practiced since the end of the last century, and is now widespread throughout the lower Mekong area of the country (Ling, 1977). From here it has spread in recent year to Viet Nam, Thailand and other Indo-Chinese countries.

A similar type of cage culture, using floating bamboo cages to grow *Leptobarbus heoveni* fry captured from the wild, has been practiced in Mundung Lake, Jambi, Indonesia since 1922 (Reksalegora, 1979), and has since been extended to other parts of southern Sumatra. Yet another form of cage culture seems to have begun independently in Java, where Vass and Sachlan (1957) reported that the capture and enclosure of carps in submerged bamboo or 'bulian' cages has been practiced since the early 1940s. Cages were usually anchored to the bottoms of small, organically enriched

streams, where the captive carp fed and grew on organic material and benthic organisms carried in the drift. However, this method of culture is still almost solely restricted to west Java and Sumatra (Sodikin, 1977), and has had little influence on cage culture practices in other countries.

1.3 CURRENT CAGE AND PEN CULTURE METHODS

In the last 15 years or so, the practice of cage culture in inland waters has spread throughout the world to more than 35 countries in Europe, Asia, Africa and America, and by 1978 more than 70 species of freshwater fish had been experimentally grown in cages (Coche, 1978a). In all but a few areas, new materials such as nylon, plastic, polyethylene and steel mesh which although much more expensive have a much longer life-span and permit better water exchange, have superceded wood and bamboo. Most designs currently in use are of the floating type, and rely on a buoyant collar constructed either from locally available materials (e.g. wood, bamboo), or from steel or plastic pipe, and from which is suspended a synthetic fibre net. Styrofoam or oil drums are frequently used for supplementary flotation.

Cages are usually floated in rafts, and either anchored to the lake/reservoir/river bottom, or alternatively connected to shore by a wooden walkway (Fig. 2).

In some parts of the world such as China and the Philippines, fixed cages are used in shallow waters (<8m) with appropriate muddy bottoms (FAO, 1983). Synthetic fibre net bags are attached to posts driven into the substrate. They are simpler and cheaper to construct as they don't involve the construction of a buoyant collar, which can account for more than 50% of the capital outlay (see IDRC/SEAFDEC, 1979). However, fixed cages are often poorly constructed, and thus may be less able to withstand adverse weather conditions. For example, in July 1983 almost all of the fixed cages in Lake Buhi, Bicol Region in the Philippines were destroyed by Typhoon Bebeng, whereas most of the floating cages survived.

There are approximately ten species of fish which are commercially cultured in cages in both temperate and tropical waters, and these are listed in Table 1.

The origins of pen culture are more obscure, but it also seems to have begun in Asia. According to Alfarez (1977) and others, pen culture originated in the Inland Sea area of Japan in the early 1920s. It was adopted by the People's Republic of China in the early 1950s for rearing carps in freshwater lakes, and was introduced to Laguna de Bay and the San Pablo Lakes in the Philippines by the Bureau of Fisheries and Aquatic Resources (BFAR) and the Laguna Lake Development Authority (LLDA) between 1968 and 1970 in order to rear milkfish (Chanos chanos) (PCARRD, 1981).

Pens are still constructed in much the same way as they always were, except that nylon or polyethylene mesh nets have replaced the traditional split bamboo fences. The nets are attached to posts set every few metres, and the bottom of the net is pinned to the substrate with long wooden pegs. Buttressing may be used to strengthen the structures in exposed areas. Pens are usually built in shallow (<10m) waters, are 3-5m deep, and 1-50 ha in size (IDRC/SEAFDEC, 1979). Soft substrates are preferable.

The development and adoption of inland water pen culture has been much less dramatic than that of cage culture, and at present it is only practiced on a commercial basis in the Philippines, Indonesia and China (Dela Cruz, 1980, 1982; Lam, 1982). The principal species being cultured in these countries are milkfish and carps (e.g. grass carp, Ctenopharyngdon idella; bighead carp, Aristichthys nobilis; silver carp Hypophthalmichthys molytrix (Table 1). Some experimental pen culture of carps has been carried out in pens in oxbow lakes in Hungary (Muller, 1979; Muller & Varadi, 1980), and other countries such as Bangladesh and Egypt have expressed interest in their use (Ishak, 1979; Karim and Haroud-al-Rashid Khan, 1982). The production of tilapias in net pens is also currently being evaluated in the Philippines (Guerrero, 1983).

Because of their smaller size (generally 1000m^2 surface area) and because they are easier to manage, cages are more adaptable than pens and can be used not only for grow-out of fish to market size, but also for breeding and fry production of fishes such as the tilapias (Pagan-Font, 1975; Rifai, 1980; Guerrero, 1983; Beveridge, 1984) and for nursing of the planktivorous juvenile stages of carps, white fish and pike (Bronisz, 1979; Jäger and Kiwus, 1980). Pens are largely restricted to lentic water bodies, whereas fixed and floating cages are also used in rivers and streams. However, in most cases both systems are used for monoculture.

1.4 ADVANTAGES AND DISADVANTAGES OF CAGE AND PEN CULTURE

Cages and pens have several advantages over other methods of culture (Table 2). Because they use existing water bodies, require comparatively low capital outlay and use simple technology, they are popular with farmers, extension workers and development programmes. They can be used not only primarily as a method for producing high quality protein cheaply but also, as is happening in Malaysia and Singapore, to clean up eutrophicated waters through the culture and harvesting of caged planktivorous species (Yang, in press; Awang Kechik et al, in press) and to improve conditions in acid lakes in Scandinavia (Swedish Research Council,1983). Thus, despite accounting for only 5-10% of current inland water aquaculture production, growth in this sector is rapid.

However, concern is growing about the environmental impact of these methods. Intensive culture is believed to accelerate eutrophication, and extensive cage and pen farming has had a record of high initial promise, followed by decreasing production figures. Subsequent sections of this report classify and review different methods of enclosure culture, discuss environmental impact and attempt to model the effects of culturing fishes in cages and pens in inland waters.

Chapter 2

LIMITATIONS OF CAGE AND PEN CULTURE METHODS

2.1 CLASSIFICATION

Cage and pen culture, like other methods of rearing fish, may be conveniently classified as extensive, semi-intensive, or intensive on the basis of feeding. Extensive culture relies solely on naturally available foods such as plankton, detritus, benthos and drift, and no supplementary feeding is given. Semi-intensive culture involves the addition of low protein (< 10%) feedstuffs, usually compounded from locally available plants or agricultural byproducts to supplement the intake of natural food, whereas in intensive culture operations, fish rely almost exclusively on an external supply of high protein (> 20%) food, usually based on fish meal.

2.2 LIMITATIONS AND PROBLEMS

There are several factors which demographically restrict the range of species grown and the methods employed. The first constraint is geographic. Primary production, which governs all successive energy transactions in the aquatic food web (Barnes, 1980), has been shown to be correlated with latitude (Brylinsky, 1980). Data derived from the summary report of the 13-year International Biological Programme (IBP) illustrates this (Le Cren and Lowe-McConnell, 1980). Between temperate (23°-67°) and tropical (23°N-23°S) zones, there is a considerable increase in the range of production values (Fig. 3) and thus tropical water bodies offer better opportunities for extensive and semi-intensive cage and pen culture.

In Europe and North America, there are few extensive operations. In the Federal Republic of Germany there is some extensive production of carps in earth ponds (Bohl, 1982). However, extensive cage culture in Europe is largely restricted to the rearing of juvenile planktivorous stages of fishes, using illumination to attract zooplankton (Bronisz, 1979; Uryn, 1979; Jager and Kiwus, 1980). In USA, recent experiments in the extensive culture of bighead carp in cages have proved disappointing, with slow growth and low survival, and thus poor economic prospects (Engle, 1982).

Extensive and semi-intensive methods are only suitable for fish which are planktivorous, or which feed on benthos, detritus or drift, and are not suitable for fish with high protein requirements or which do not have the anatomical, physiological or behavioural adaptations to deal with these types of food. Carnivorous species, such as the salmonids and many of the catfishes (e.g. Ictalurus punctatus, Pangasius sutchi) cannot be successfully grown without recourse to intensive methods, using largely fish protein based diets (see Cowey, 1979, for review). Although all of the tilapias have comparatively low protein requirements and many therefore appear suitable for extensive cage culture, this is not so. All tilapias possess both jaw teeth and pharyngeal teeth, and these vary in

size, structure and mobility (Trewavas, 1982), thus influencing the type of diet and particle size they can deal with. Microphagous species, such as O. niloticus, O. mossambicus and O. aureus grow better in extensive culture than do the macrophagous species, T. zilli and T. rendalli (Coche, 1982; Pullin, in press).

There are major differences between pens and cages, and between lotic and lentic sites in terms of availability and types of natural feeds. Fish grown in pens have access to benthic organisms, and there is some evidence that certain species grow better in pens than in cages. It is probably for these reasons as well as because of their size that there is no intensive culture in pens. In both temperate and tropical waters, primary production is generally lower in lentic than in lotic sites (Fig. 3) and energy inputs are dominated by allochthonous (external) rather than autochthonous (internal) inputs (Minshall, 1967; Knoppel, 1970; Fisher and Likens, 1973; Dudgeon, 1982). Autochthonous production in flowing waters is primarily by attached plants - macrophytes, periphyton - with little contribution from the small plankton community, and organic matter is processed by the detrital and benthic micro- and macrofloral and faunal communities (Fahy, 1972; Dela Cruz and Post, 1977; Blackburn and Petr, 1979; Dudgeon 1982a). There are thus few plankton-feeding fishes in most running waters, and cage culture of such fishes without supplementary feeding is likely to be impractical. Recent experiments in Tengi River, Malaysia, with extensively cultured bighead carp have confirmed this (Othman, et al, in press). Cages were stocked with 25.3g fish at a stocking rate of 15 fish m^{-3}. During the 2 month trial 95% of the carp died, and the average weight of the survivors was 19.5g.

Under some circumstances, however, planktivorous fishes may be grown in running water. At the head waters of the Bicol River in the Philippines, where it flows out of Lake Buhi, the plankton discharged from the lake is sufficient to permit the rearing of caged O. niloticus without supplementary feeding (Job Bisuña, pers. comm.) (Fig. 4).

Small rivers enriched with some organic material will have larger benthic populations and carry more detritus and insect life in the drift, than in polluted streams. Such sites are probably best for extensive/semi-intensive culture of omnivores such as carps and catfishes, as is practiced in Indonesia and Thailand (Vass and Sachlan, 1957; Ling, 1977). Heavily polluted sites, however, are not suitable due to low O_2 levels which can retard growth and cause fish kills.

In fast-flowing rivers, however, intensive or semi-intensive fish culture is not advisable due to excessive loss of feed. Although losses can be reduced by using a feeding ring (Coche, 1979), slow-flowing lowland or delta sites are preferable.

There are also economic and technical considerations which greatly influence the extent and methods of cage and pen culture practiced in inland waters in different regions of the world. Whilst the reasons for intensification are clear - increased production per unit water use, reduced labour costs, etc. - the use of intensive enclosure culture is only feasible if the fish being cultured realise a sufficiently high price to generate a profit when harvested. According to recent data published by ADCP (ADCP, 1983), feed represents 40-60% of the total operating costs in intensive aquaculture. However, in order for the venture to be profitable, ADCP recommend that feed costs do not exceed 20% of the farm gate value of the fish. This is the case in Western Europe and North

America where the intensive culture of carnivorous salmonids and catfishes is feasible due to the high market prices these fish demand. However, this is not the case in the tropics. Although intensive feeds for fishes such as the tilapias and Indian major carps have been developed (Jauncey and Ross, 1982; ADCP, 1983), there has to date been little commercial interest. In 1982 in Laguna Province in the Philippines, for example, the price paid by retailers for tilapia was between ₱7.55 and ₱11.50 per kilo, depending on size of fish and season (Aragon et al, 1983), whereas in Bicol Region, the price varied between ₱3.75 and ₱5.40 (Escover et al, 1983). According to ADCP guidelines, therefore, intensive feedstuff prices must remain between ₱1520 and ₱2300 (US$100 - US$150) per tonne in Laguna, and ₱750 and ₱1080 (US$50 - US$72) per tonne in Bicol, which is well below the production costs of US$320 per tonne estimated by ADCP for a 27% protein diet suitable for intensive culture of tilapia (ADCP, 1983). Similar prices for tilapias and carps occur in many other tropical countries, and therefore intensive feeds are not yet a widely available option. Exceptions to this can be found in some countries in Southeast Asia. For example, a wide range of tilapia feeds of variable quality is available in Taiwan, where nearly all tilapia culture is intensive (R.S.V. Pullin, pers. comm.).

Technical problems of feed manufacture and storage can hamper the development of intensive cage and pen culture which has been proven economically viable, and this is particularly true in the tropics. For example, expansion of the intensive cage culture of rainbow trout in Bolivia faces problems due to the poor quality of commercially available diets (Beveridge, 1983). Contamination of feeds by aflatoxin-producing species of Aspergillus has also been reported as causing problems in tilapia farms in Africa and Southeast Asia (Roberts, 1983; Olufemi et al, 1983).

In many areas of the world, fry and fingerling production is the main technical problem yet to be overcome. The culture of many species, such as the milkfish, Chanos chanos, in the Philippines, Taiwan and Indonesia is still dependent upon the seasonal collection of fry from the wild, despite successful spawning in laboratory conditions (Liao and Chen, 1979; Lam, 1982; PCARRD, 1982). Over-exploitation of wild fry in some areas has led to shortages, high prices, and put a brake on the growth of the industry.

As fish culture industries expand, output from hatcheries must keep pace with the demand from producers. In the Philippines, a tremendous increase in interest in the cage culture of tilapias over the past five years has resulted in a greatly increased demand for fingerlings (Guerrero, 1982). Although hatchery production is keeping pace, concern is growing about the huge volume of fingerlings being produced from back-yard hatcheries (Pullin, in press.) Farmers buying slow-growing fry put their businesses at risk, and BFAR are currently trying to minimise the risk of this happening by supplying commercial hatcheries with good-quality broodstock from their hatchery at CLSU, Nueva Ecija (Broussard et al, 1983).

Most of the above problems are common to both land-based (e.g. ponds, tanks, raceways) and water-based aquaculture. However, there are several problems which are peculiar to cage and pen culture, and which have caused the collapse or arrested the development of the industry. In several instances in the Philippines cages and pens have been established in highly eutrophic lakes, where regular fish kills occur through deoxygenation of the water following the collapse of algal blooms, and the

subsequent decomposition of the algae (Barica, 1976; PCARRD, 1981). In Laguna de Bay, regular fish kills have occurred almost every year since the early 1970s, the worst being in 1975 when 5×10^6 milkfish were killed. By 1981, 73% of fishpens in the lake had experienced fish kills (PCARRD, 1981).

Toxic industrial pollution may also cause problems. In November 1983, 150 ₱ million worth of milkfish and tilapia in 30 ha of fish pens and cages in the western part of Laguna de Bay were killed by the appearance of "masamang tubig", or highly polluted water (Source: Bulletin Today, Nov. 10 1983). The polluted water was described as black and oily in appearance, and blamed by local fishermen on industrial sources.

Other problems experienced by the cage and pen industry include damage during storms etc. and theft and vandalism (Coche, 1979, 1982; PCARRD, 1981). In the Philippines in July 1983, Typhoon Bebeng devastated large numbers of lake-based fish farms in Bicol, Laguna and Rizal Provinces in South and Central Luzon, and many of the operators have been unable to rebuild their farms since, due to the prohibitive costs involved.

Theft and vandalism have been cited by cage tilapia producers in the Philippines as the major problem they encounter (Escover and Claveria, 1983). Although farms are unlikely to close for these reasons development may be restricted, since operators are often unwilling to site their enclosures far from their homes, and viability may also be affected through increased expenditure on security.

2.3 DISCUSSION

Intensive cage and pen culture of fishes is largely restricted to temperate, developed regions, where luxury carnivorous species are grown on expensive, high-protein feeds compounded from fish meal. Intensive feeds are not essential in tropical fish culture, since many of the commercially important species such as the tilapias, carps and milkfish feed readily on natural macrophyte, plankton and detrital production. Supplementary feeds derived from low-cost, low-protein agricultural by-products or wastes, are widely used in order to improve production. There are some technical problems which retard the development of intensive feeds. However, even in countries where complete diets suitable for intensive feeding have been formulated, such diets are generally not in common use since they are too expensive (Guerrero, 1982). Most of the popularly-cultured species have low retail prices, with small profit margins for the producers.

One of the few exceptions seems to be Taiwan, where a large number of commercial brands of feed for tilapia and milkfish are available (R.S.V. Pullin and J. Kuo, pers comm.). However, Taiwan is a sub-tropical country with a limited season for the growth of tropical species, and limited land and water resources for aquaculture development. Thus intensive fish rearing makes economic sense. Also, middle-class consumers (of which there are a large number) are willing to pay more for fish which are intensively reared and which do not have the muddy taste often associated with fish reared in extensive or semi-intensive earth pond and lake conditions (J. Kuo, pers. comm.). Intensive cage and pen culture may also become viable in the tropics if the farming of high-priced,

carnivorous species such as Marble-headed goby (Oxyeolotris marmorata) develops, or if intensive and semi-intensive/extensive culture are practiced at the same site (see Section 5 below).

The supply of quality fry to certain sectors of the industry, as well as adverse weather conditions, theft, vandalism and pollution, also take their toll and affect the development and viability of cage and pen culture in different parts of the world. Lentic systems seem to offer the best potential for enclosure culture. Organically enriched streams and slow-flowing stretches of rivers offer some potential for semi-intensive culture, although low plankton concentration precludes most forms of extensive culture, and the comparatively high flow rates, with their associated feed losses, make intensive cage or pen culture impractical.

Chapter 3

ENVIRONMENTAL IMPACT

3.1 INTRODUCTION

The introduction of cage or pen culture to a water body has an impact on the environment which can lead to conflict, since inland waters are often, and increasingly so, under pressure from other users and for a wide variety of purposes. It can induce the operation of negative feedback mechanisms which restrict the number of units, determine the type of species grown, and limit production. The establishment of cage and pen farming operations in a lake, reservoir or river can also have an impact outside the immediate vicinity of the site, by its demands for construction materials (Cariaso, 1983) (see Section 3.3.3 below).

Enclosures can affect water bodies both by their physical presence at a site and by the changes they can induce in the physical, chemical and biological characteristics of the water body through the method of culture (extensive/semi-intensive/intensive) and species used.

3.2 THE IMPACT OF ENCLOSURE STRUCTURES ON THE ENVIRONMENT

Cage and pen structures affect a water body in three principal ways: they take up space, thus potentially competing with other users; they alter flow regimes which govern the transport of oxygen, sediment, plankton and fish larvae; they have an impact on the aesthetic qualities of the site.

3.2.1 Space

Enclosures can compete with lake and river fisheries for space. Stationary cages and pens, for example, are restricted to shallow areas, which are 7m or less deep, and this approximates to the littoral region of most lakes and reservoirs where rooted emergent and submerged vegetation occurs (Goldman and Horne, 1983). Such areas are important as spawning grounds for commercially important fishes such as the phytophilous cyprinids and pike (Braum, 1978), and the substrate spawning tilapias, T. zilli, T. rendalli and O. macrochir (Ruwet, 1962; Philippart and Ruwet, 1982). Inshore areas of vegetation where predators can be avoided are also important nursery grounds for fry and juveniles of many species.

In Laguna de Bay in the Philippines, pen and cage culture of milkfish and tilapias was introduced in the late 1960s (PCARRD, 1981). Since then these industries have boomed, despite the ravages of periodic typhoons and fish kills (Fig. 5). The LLDA has attempted to regulate the industry and avoid conflict with fishermen and local villagers by trying to limit production within certain areas of the lake designated as a fish pen belt by a series of laws (Republic Act No. 4850, Presidential Decree No. 813, and Resolution No. 9, 1976; Agbayani, 1983). The fish pen belt provides for other interests by leaving free a fish sanctuary area, where

no fishing or pens are permitted, and by utilising a 15,000 ha area (17% of the lake surface) which is at least 200m from the shore and yet does not interfere with navigation routes (Fig. 6). Thus access to inshore areas, open waters and fish landing sites should have been protected.

However, in the last 3-4 years, there has been a rapid proliferation of fish pens outside the legal fish pen belt (Figs. 7 and 8). The use of cages to culture tilapia is not covered by existing laws (Agbayani, ibid.), and although still of relatively minor importance (100ha; Guerrero, 1983), they are increasing. Current estimates of the area covered by cages and pens is 34-40,000 ha (38-45% of the lake).

Many of these illegal enclosures were sited in traditional fishing grounds and snail-gathering areas, and blocked the main navigation routes to the fish landing sites (see Fig. 8). In 1982 and early 1983 the widely reported conflict (theft, vandalism, killings) between the local fishermen and the fish pen owners, most of whom live outside the Laguna de Bay area, had escalated. Following public pressure, an aerial survey of the lake was carried out by the Philippine Air Force in April 1983, and when the extent of the proliferating pen industry was realised, existing regulations were enforced.

Not all impacts of enclosure structures may necessarily be negative. The attraction of fishes to free-floating and anchored objects has been widely reported from all over the world, both in freshwater and marine situations. Many of the theories proposed to explain these phenomena apply to the effects of cage and pen structures on wild fishes, and are summarised in Table 3. In Laguna de Bay, the numbers of the indigenous catfish, kanduli (Arius manilensis), had been declining for some years prior to the establishment of the cage and pen industry, due to pollution and overfishing (Santos, 1979). However, the enclosures have apparently provided shelter for the fish, thus allowing the population to recover somewhat (Guerrero, 1982a).

Snails (Lymnea and Amnicola spp.) which are intensively harvested for feed for the local duck industry (Arriola and Villaluz, 1939), are reported to have increased to high densities within the protection of the pens (Guerrero, 1982a). However, there is also evidence that these enclosed snail populations fluctuate enormously, because of unchecked growth and recruitment,and restrictions on emmigration from the area (S. Vivar, pers. comm.). Whilst some fish pen owners do permit snail gatherers to harvest their pens for a fee, others refuse, arguing that the type of fine-meshed gear in use on the lake is highly destructive and disruptive.

3.2.2 Water flow and currents

The flow of water through enclosures is affected by drag forces exerted by the framework and netting (Inoue, 1972; Wheaton, 1977; Milne, 1979; Wee, 1979). The reduction in flow is dependent upon a number of variables including flow rate and density of water, enclosure size and shape, mesh type (knotted/knottless, diamond/square) and material, degree of fouling, and stocking density (Milne 1970, 1979; Inoue, 1972; Wheaton, 1977, Wee, 1979; Kils, 1979). The coefficient of drag (Cd) exerted by knotted and knottless netting is related to nominal mesh size (a), and diameter of twine (d) by the following equations (Milne, 1970):-

$$Cd = 1 + 3.77\ (d/a) + 9.37\ (d/a)^2 \qquad \text{knotted net}$$

$$Cd = 1 + 2.73\ (d/a) + 3.12\ (d/a)^2 \qquad \text{knottless net}$$

Cd is greater for knotted than knottless mesh, and courlene and polythene have smaller Cd values than nylon or ulstron (Milne, ibid.).

Inoue (1972) noted that the current velocity inside a large (20 x 20 x 6m) cage of 5cm mesh size, stocked with fish at 1.6 kg m^{-3} fell to only 35% of the current speed recorded outside the cage, and he also demonstrated that when cages were located parallel to the direction of current, flow rate in successive cages fell.

Cage and pen structures, therefore, can have a considerable impact on local currents, and this has a number of implications. Sediment transportation in an aquatic system, although influenced by a number of factors, is principally determined by current flow (Smith, 1975; Gibbs, 1977). Significant reductions in flow, as can occur in some enclosure systems (see above), would cause the sedimentation of larger, denser particles in the immediate vicinity of the cages and pens. A sudden increase in the rate of sedimentation in an area would disrupt benthic communities (Brinkhurst, 1974) and accelerate filling in (ageing) of the water body, which could interfere with navigation. Siltation in the vicinity of cages and pens has been reported from Egypt, India, Malaysia, Singapore, Sri Lanka and Thailand (IDRC-SEAFDEC, 1979).

Siltation problems caused by enclosures are most likely to occur in rivers and in areas of lakes where large rivers flow in. Here the dispersion of the sediment carrying plume, which is determined by the horizontal water current speed (Csanady, 1969, 1975) could be severely disrupted.

Of more importance, however, are the effects of reduced current on the fish culture operation. The flow of water through the system governs the supply of oxygen and the removal of toxic waste metabolites from the vicinity of the fish, and in extensive and semi-intensive culture, it also controls the supply of planktonic food.

3.2.3 Aesthetics

The introduction of cages and pens to a water body can transform its appearance (Fig. 4). In many countries, provision is made within conservation laws to preserve areas of outstanding natural beauty, and protect them from unsightly developments. The proposed establishment of a large floating cage fish farm in Loch Lomond, Scotland, by a private company was objected to by a number of people who thought that this would detract from the scenic value of the area, reduce tourist numbers estimated at 2 million per year, and ultimately affect local employment and incomes (Beveridge and Muir 1982). Similar objections have been voiced over cage culture developments in Hong Kong.

3.3 THE IMPACT OF ENCLOSURE CULTURE METHODS ON THE ENVIRONMENT

The introduction of cage and pen culture to inland waters can cause a number of changes to both the biotic and abiotic components of the environment. Although intensive, semi-intensive and extensive methods of culture have impacts which differ both qualitatively and quantitatively from one another and will therefore be considered separately, there are a number of factors common to all methods, and these will be examined first.

3.3.1 Environmental impact common to all methods of enclosure culture

An enclosure is more of an open fish rearing system than land-based ponds, raceways or tanks, and there is a far greater degree of interaction between the caged or penned fish and the outside environment than occurs in other systems. In recycle systems, only 1-20% of the daily water requirements are replenished (Bryant et al 1980; Muir, 1982; Muir and Beveridge, in press). Incoming water passes through settlement tanks and filtration systems which effectively remove all bacteria, protozoa and plankton, and of course larger organisms such as fish. In some operations, the recycled water is treated by U.V. which kills most of the virus particles and remaining bacteria in the system (Spotte, 1979; Muir, 1982). Thus there is little opportunity for organisms to enter and influence the system from outside, and the fish are cultured in an environment where both the abiotic and biotic components are highly controlled.

In earth and concrete ponds, the fish are fully exposed to the vagaries of climate (sunlight, temperature etc.), and there is also a degree of interaction between the cultured fish and other organisms. Usually, only coarse screens and/or settlement ponds are used, which help prevent fishes (eggs, fry, adults) from entering the system (Hepher and Pruginin, 1981). However, microscopic and macroscopic organisms such as viruses, bacteria and fungi, and phytoplankton, zooplankton and insects can be carried unimpeded into the ponds in inflowing water. Birds and other vertebrates also have relatively free access to ponds and raceways unless elaborate trapping or other preventative methods are used (Meyer, 1981; Martin, 1982).

The establishment of recycle systems and ponds and raceways to grow fish is the creation of a new environment. However water usually only passes through pond and raceway systems once, and the consequences of changes to the water through fish culture is experienced where the effluent is discharged. Outflows from land-based systems of course can be treated by passing water through various settlement pond and filtration systems until acceptable standards are reached (Warrer-Hansen, 1982; Muir, 1982a). By contrast, enclosures use existing environments to grow fish. Cages and pens must thus be regarded as subcomponents of the aquatic ecosystems in which they are sited, since the enclosure and the surrounding environment are intimately related i.e. changes occurring in the water body will have an effect on the enclosure environment, and vice versa. There is little opportunity to treat wastes emanating from cages. Although various methods of waste collection and removal have been developed on an experimental basis (Tucholski et al, 1980, 1980; Tucholski and Wojno, 1980) the costs involved would prove prohibitive to the industry. These differences between land and water based systems have a number of important implications.

3.3.1.1 Disease

There are five main groups of organism which cause disease in fishes: ectoparasites and fungi, endoparasites, bacteria, viruses and organisms which produce toxins leading to fish deaths (Sarig, 1979). The occurrence of disease outbreaks in fish farming is usually asociated with bad husbandry, since the disease-causing organisms are often ubiquitous and cause few problems until the fish are stressed through inadequate dietary or environmental conditions (Wedemeyer, 1970; Snieszko, 1974; Roberts and Shepherd 1974; Shepherd, 1978). In wild fish populations, mass mortalities are rare and are also usually linked to external stress factors (Shepherd, ibid.), since the fish and the disease causing organisms are usually in a state of balance. For example, although many parasitic infections are known in wild tilapias, there is little evidence of clinical effects and thus it would seem that the presence of parasites is a normal occurrence of little significance (Roberts and Sommerville, 1982). Studies of the adult cestode Eubothrium in rainbow trout show that 1-5 parasites per fish have no effect on either nutrient absorption or fish growth (Ingham and Arne, 1973).

However, the introduction of large numbers of fish in enclosures to a system can have a dramatic effect on disease agents. Diseases from outside the enclosure site can easily be introduced by transporting fingerlings/fry from other areas in the country, or importing fish from abroad wthout proper precautions being taken (Avault, 1981; Mills, 1982). The danger of the spread of fish diseases in this way is widely recognised, and is currently giving cause for concern (Rosenthal, 1976; Roberts and Sommerville, 1982). In a recent survey of the ecto and endoparasite fauna of cage and wild fish communities in a Scottish loch, Sommerville and Pollock (1984 in prep.) have shown that the numbers and species of parasite present in the wild fish differ markedly from expected, and concluded that this was a result of the intensive culture of rainbow trout in the lake. Although some of the parasites may have been imported with fingerlings used in stocking, yet others may have been present in the wild fish and only reached abnormal levels due to increased densities of fish and changes to the environment subsequent to the introduction of cages.

Unfortunately, little is known about the transmission of parasites from cage to wild fish, or vice versa. However, in several cases in the U.K., cage fish have become severely infested with the cestodes Triaenophorus nodulosus and Diphyllobothrium spp. resulting in heavy mortalities, and the eventual closure of one farm (Wootten, 1979; Jarrams et al, 1980). Those infections were attributed to the wild fish populations which were subsequently found to be carrying the parasites.

Data from Matheson (1979) showed that Atlantic salmon parr raised in cages in a freshwater loch in Scotland became heavily infected with D. ditremum and D. dendriticum within two months of being introduced to the site. Surprisingly, the parasites were not isolated from the brown trout (S. trutta) in the loch, although only a few specimens were examined.

A survey of fishes in a Scottish lake site prior to the introduction of cages showed no endoparasites present, and one month later cages of rainbow trout were introduced. The stocked trout were also examined and found to be free from parasites. However, two months later mass mortalities of fish were reported, and on examination the fish were found to be heavily infected with Diphyllobothrium spp. (Sommerville, unpublished

data). Phillips et al (1983) believe infestation was precipitated by inadequate use of feed, which caused the caged fish to ingest copepods, the intermediary hosts for these cestodes.

The role of increased nutrient levels often associated with intensive cage culture (see below) in promoting proliferation of parasites is not clear. However, Grimaldi et al (1973) have shown that Phycomycetes saprolegnioles infections of trout are widespread in eutrophic lakes in central Italy and northern Switzerland. Eutrophic conditions may also favour increased production of intermediary hosts (e.g. crustaceans). Recent work carried out by Soderberg et al (1983) in North America, has shown that exposure of rainbow trout to high levels of free ammonia, such as can exist in intensive culture conditions, predisposed the fish to succumb to parasitic epizootics.

Few such parasite or disease problems have been reported in cage or pen culture of fishes in the tropics, although Vass and Sachlan (1957) reported the presence of gut parasites in common carp grown under extensive conditions in a polluted Indonesian stream. These parasites were believed to have been transmitted from human faeces.

3.3.1.2 Predation

Cages and pens of fish seem to act as a magnet to a wide range of both obligate and facultative fish-eating vertebrates. The range of species reported to cause problems at cage and pen farms is listed in Table 4, and includes fish, reptiles, birds and mammals. Many of these species move into an area where a fish farm has been established, attracted by the large numbers of readily detected fish and also by the bags of commercial feed occasionally left unprotected on the cage walkways. Even comparatively rare species, such as the osprey (Pandion haliaetus) in Scotland will travel considerable distances in order to visit a fish farm. Seasonal and diurnal changes in numbers of predators have been noted (Ranson and Beveridge, 1983).

So far there has been little serious evaluation of the impact of these predators either on the environment, or on the enclosed fish. Ranson and Beveridge (1983) concluded that although herons (Ardea cinerea) and cormorants (Phalacracorax carbo) frequently attacked caged rainbow trout, these attacks were rarely successful. An examination of stomach contents of birds from the farm showed no evidence that any of the fish came from the cages, and this conclusion was supported by many hours of observation. However, 0.5% of all caged fish showed evidence of bird damage, which could lead to secondary bacterial or fungal infection.

Damage to nets by unsuccessful predators such as birds, turtles, monitor lizards and rats has been reported from several cage farms (Table 4), thus contributing to the heavy losses of fish from enclosures reported by Secretan (1979). Predation of wild fish may increase through the attraction of predators to the enclosure site. Ranson and Beveridge (1983) recorded 11 perch (Perca fluviatilis) removed from a cormorant stomach at a cage fish farm. Another serious, although as yet little studied, impact of the immigrant predator population, is their contribution to disease. In the example described in Section 3.3.1.1 above, the rapid spread of Diphyllobothrium to caged rainbow trout within two months of a farm being established may in part be due to the observed migration of large numbers

of gulls (Larus sp.) into the area. Certainly both birds and mammals play important roles in the life cycles of many commercially important endoparasitic fish diseases. For example, birds act as intermediate host in the life cycle of the nematode Contracaecum, and piscivorous mammals such as the otter may act as final host for the digenean Haplorchis, both common parasites of tilapia (Roberts and Sommerville, 1982).

3.3.1.3 Wild fish populations

Caged and penned fish frequently escape through netting or mesh damaged by predators, floating objects, or rough weather (Secretan, 1979), and in this way foreign or exotic species can be introduced to an environment. In any commercial cage or pen operation it is inevitable that some fish escape. In one lake in Poland, Penczak (1982) estimated that 4 tonnes of trout escaped in one year. There are many records of the impacts of escaped or deliberately transplanted fishes on indigenous fish stocks, and these include the extermination of local fishes through predation or competition, interbreeding with native fishes and adulteration of the genetic pool, habitat destruction and the outbreak of disease epidemics (Rosenthal, 1976; Mills, 1982).

In Laguna de Bay, typhoons often cause considerable damage to fish pens (PCARRD, 1981). In 1976, 50% of the fish pens were totally destroyed, resulting in the release of millions of milkfish to the lake (Gabriel, 1979). This boosted open water fishery catches tremendously in the weeks following the disaster.

In the U.K., ferral rainbow trout which had escaped from cages were found to be breeding in feeder streams to the lake. Examination of the gut contents showed that the rainbow trout and native brown trout fry in the streams had similar diets, and therefore could be competing. Angling catch returns from the lake demonstrated that brown trout returns, which had declined to a low level many years previously, remained low after the introduction of the cages, whereas the catches of rainbow trout increased each year due to escapes (Phillips, unpublished data).

3.3.1.4 Toxic chemicals and drugs

The use of chemicals and drugs in pond, tank and raceway fish farms to control disease is widespread, particularly in intensive units in North America, Europe, Israel and Southeast Asia (Bardach et al, 1972; Brown, 1977; Hepher & Pruginin, 1981; Alabaster, 1982a). In the most extensive surveys to date, carried out in Europe and the U.K., Alabaster (1982a) and Solbe (1982) found that most pond, tank and raceway farms used small amounts of chemicals (especially malachite green and formalin) from time to time to treat ectoparasitic and fungal infections. A wide range of antibiotics, such as aureomycin, furazolidene, nitrofurazone, penicillin, oxytetracycline, sulpha-merazine and terramycin are also occasionally administered to fish in their food.

However, there is very little quantitative data on the frequency or pattern of use of chemicals and drugs in cage and pen farms. Treatment is costly and difficult due to water flow through the enclosures which can rapidly dilute the chemical used, and render treatment ineffective. The

addition of large quantities of chemicals to compensate can make treatment too costly. To minimise expense, many farmers enclose cages in polythene sheeting to try and reduce the flow rate, although this is highly labour-intensive. Alternatively, they transfer diseased fish to a specially modified enclosure or tank, thus minimising waste (i.e. loss to the environment) of chemicals. For these reasons, it is probable that chemicals on enclosure farms are employed much less frequently than in other systems, and the resultant additions of foreign substances to lakes etc., is small.

3.3.2 Problems associated with intensive culture

Intensive culture of fishes in enclosures, as discussed in Section 2 above, is at present largely restricted to lakes and reservoirs in temperate regions, where the principal farmed species are salmonids, carp and catfish. Early laboratory studies by Murphy and Lipper (1970) and Liao (1970) demonstrated that the intensive culture of fish resulted in high levels of waste production per unit live weight, compared to other livestock such as chickens, swine or cattle. As the cage industries developed and expanded in the 1970s, concern about the potential polluting effects grew.

The first studies of environmental impact of intensive cage culture were in the United States, where the Arkansas Game and Fish Commission had begun leasing areas of state-owned lakes and reservoirs to commercial catfish and trout producers in the early 1970s (Eley et al, 1972; Newton, 1980). As their lease programme expanded, a number of studies were commissioned (Eley et al, 1972; Kilambi et al, 1976; Hays, 1980). In Eastern Europe, intensive culture of common carp and trout has been practiced in lakes used as cooling ponds for heated water from power stations since the mid-1960s (VNIRO, 1977), and the water quality of several of these lakes has been monitored over a period of years (Korycka and Zdanowski, 1980). Recent studies in Poland have been concerned with the waste output of caged rainbow trout in reservoirs (Tucholski et al, 1980a, 1980b; Penczak et al, 1982).

In the U.K., two study programmes on the environmental impact of intensive cage rainbow trout farming are in progress at the Institute of Aquaculture, University of Stirling. One is a long term monitoring programme of water quality at a highly developed commercial site in a lowland reservoir, and the other concerns the study of environmental impact of intensive culture on the more typical dystrophic-type of lake that is currently being developed for cage culture in highland Scotland (Phillips et al, 1983). A desk study has also been completed on the impact of proposed cage culture developments on Loch Lomond, an important natural reservoir and Site of Special Scientific Interest in Central Scotland (Beveridge and Muir, 1982; Beveridge et al, 1982).

Several other study groups are currently studying the problems at the University of Lund, Sweden (Enell, 1982; Anon, 1983), and at the Department of Agriculture and Fisheries, Scotland, in Pitlochry (R. Harriman, pers. comm.).

In general, these studies fall into two categories. In some investigations, comparisons have been made between the environment at the cage site, and at a control site some distance from the cages, whilst in

others, a study of the site prior to the introduction of cages, and during and after the period of culture have been carried out (Kilambi et al, 1976; M. Phillips, pers. comm.). The latter type of study, is preferable, but involves planning, long term commitments of manpower and resources, and of course greater capital than a short-term study.

However, irrespective of differences in methodology, species cultured and size and type of site, most studies have recorded increases in the levels of suspended solids and nutrients (alkalinity, total-P, PO_4-P, NH_4-N, organic N,C) and decreases in O_2 in and around the enclosures (Table 5). In the sediments below cages, considerable increases in oxygen consumption and in the total-N, total-P and organic content of the muds has been recorded (Tucholski et al, 1980; Enell, 1982; Merican, 1983). (See Fig. 9).

Changes in the flora and fauna of inland waters associated with enclosure culture were first noted by Vass and Sachlan (1957), who investigated the effects of extensive carp culture on stream biota. More recent studies of intensive systems in temperate countries have noted quantitative and qualitative changes in bacteria, protozoa, plankton, benthos and fish (Table 5).

Changes in fish communities at intensive culture enclosure sites are inevitable, not only because of the high probability of fish escaping from the enclosures and the risks of disease introduction or escalation, but also because of the release of nutrients and loss of feed to the environment associated with intensive operations. Feed losses have been reported by many authors (Collins, 1971; Eley et al, 1972; Coche, 1979; Muller and Varadi, 1980; Beveridge and Muir, 1982; Penczak et al, 1982), and are dependent upon quality and type of food (wet/dry, floating/sinking), method of feeding (hand/demand feeders/automatic feeders), enclosure design (cage/pen; presence/absence of feeding ring; solid/mesh cage bottom) species, site characteristics (lotic/lentic; sheltered/ exposed), and stocking density (high/low). Loss of feed to the environment is sometimes increased by the currents generated inside enclosures by feeding fish (Collins, 1971; Coche, 1979).

Wild fish have been observed in comparatively high densities in the immediate vicinity of fish cages (Collins, 1971); Eley et al, 1972; Loyocano and Smith, 1976; Hays, 1980). Using telemetry, Ross, Phillips and Beveridge (unpublished data) followed the behaviour of ferral rainbow trout in a Scottish loch where intensive cage culture was in operation, and found that during certain periods of the year at least, the fish spent comparatively long periods of time near the cages. Phillips (1982, 1983) has shown that fish can learn to come to a feeding station in a lake in response to an acoustic signal, and it may be that the feeding response of the enclosed fishes acts as a signal to the wild fish that food is available.

Growth rates, and abundance and survival of fish in some lakes and reservoirs where intensive culture is practiced, have been shown to increase (Loyacano and Smith, 1976; Kilambi et al, 1978; Hays, 1980) and although this is in part due to intake of commercial feed, it is also due to the effects of increased nutrient levels. Fish growth has been found to increase in many temperate water bodies following fertilisation (Weatherly and Nicholls, 1955; Munro, 1961). However, in other lakes the intensive culture of fish in cages has resulted in a decrease in the natural fish population (Penczak et al, 1982). All water bodies have

characteristic fish communities which are dependent upon the trophic state (Vaughn et al, 1982) and changes in the trophic state will cause the fish community to change (Welch, 1980).

Negative feedback from changes in water quality on the growth and survival of caged fish have been reported from many intensive cage farms. In Lake Kasumigaura in Japan, the intensive cage carp industry has been affected by deteriorating water quality caused in part by the fish culture operation itself (Kitabatake, 1982). Interestingly, those farms using automatic feeders had significantly higher mortalities than those which practiced feeding by hand. In Scotland, off-flavours in the cultured fish, associated with the presence of high levels of blue-green algae, have been recorded from a eutrophic cage rainbow trout farm site (A. Stewart and A. Hume, pers. comm.).

3.3.3 Problems associated with extensive and semi-intensive enclosure culture

Commercial extensive culture of fishes in enclosures is restricted to tropical and subtropical countries, where fish such as milkfish, tilapias and carps can be grown without recourse to the use of supplementary feeds. In the Philippines, tilapia production of up to 2 kg m^{-3} $month^{-1}$ has been attained in this way (Table 6). The exploitation of inland waters for extensive culture follows a typical pattern: following the first and usually highly successful harvest of fish, existing entrepreneurs expand production, and other operators move in. Within a few years, there is a considerable number of both small and large operations. By the second or third year, the growth rate of the fishes has fallen, and fish farmers must either endure reduced production, or resort to the use of supplementary feeds. In both cases, economic viability is impaired and many producers may be forced to close. For those that remain, prospects usually improve (see Fig. 10).

There have been few studies which have specifically investigated the relationship between extensive cage culture and productivity. However, Henderson et al (1973), Melack (1976), Oglesby (1977, 1982) and Marten and Polovina (1982) have shown that there is a positive relationship between fishery yield and aquatic productivity, and a similar relationship seems to hold for extensive cage culture and productivity (see Section 4.4 for detailed discussion). In Seletar Reservoir, Singapore, where bighead carp have been stocked in cages since 1972 in order to combat the problems of eutrophication, there has been a steady decline in the frequency of algal blooms and plankton biomass corresponding to a decrease in fish production per unit area per unit time (Yang, in press). Aquino's study (1982) showed the growth rate of caged tilapia in Sampaloc lake in the Philippines was related both to gross primary production (Figure 11), and to visibility (i.e. related to algal biomass).

The best documented examples of the effects of such feedback mechanisms on fish culture come from the San Pablo lakes area, Rizal Province, in the Philippines. Here five of the seven lakes are utilised for pen and cage culture of O. niloticus. At Sampaloc Lake, for example, the annual production by extensive means fell from 11.4 kg m^{-3} in the late 1970s to 1 kg m^{-3} in 1983 (Coche, 1982; Guerrero, 1983). Stocking density was reduced from 25 m^{-3} to 2 m^{-3}, and the growing period to produce marketable fish (200g) increased from 4 months to 6-9 months, and many operators began to use supplementary feeds, such as rice bran, copra cake, pig manure and kitchen scraps (Aquino, 1982). Similar

problems have occurred at most of the other San Pablo lakes, although to a lesser extent. For example, 150-200g fish could still be grown in Lake Calibato in 5-6 months in 1983 without resorting to the use of supplementary feeds.

Similar problems have also beset the semi-intensive enclosure culture industry. Experience from many Southeast Asian countries shows that a period of rapid and uncontrolled expansion usually follows the introduction of cages and pens to an area leading to increasingly heavier dependence on supplementary feeding. In Laguna de Bay, fish cage and pen operators are increasingly having to rely on supplementary feeds, whilst production has fallen from 0.18-0.36 kg m^{-3} $month^{-1}$ to 0.12-0.14 kg m^{-3} $month^{-1}$ (Mane, 1979; Lazaga and Roa, 1983).

Pens and stationary cages are commonly used in extensive and semi-intensive operations in Southeast Asia (e.g. Philippines, Indonesia, China, Thailand).

Construction can require large quantities of timber, such as bamboos (Bambusa spinosa), "anahaw" palms (Livistonia rotundifolia) and hardwoods. These materials have only a limited useful life before they must be replaced. Exposed parts usually deteriorate first through the combined action of heat, sunlight and rain, and the rigours of day to day use. Lifespan not only depends upon the climate and materials used, but also on the age and health (e.g. degree of insect damage) of the wood, and the maturation and preservation method used, if any (e.g. use of pitch) prior to installation. Details of materials and their characteristics are given in Table 7.

Despite the many advantages of using other materials (stronger, longer life etc) bamboo is still the most commonly used construction material for pens and cage frames in Southeast Asia due principally to its comparatively low price and availability. It normally lasts only 1-2 years, before being replaced (IDRC/SEAFDEC, 1979). In Laguna de Bay in the Philippines, some of the old wood is removed by local villagers for use as firewood, although most is left in the lake to decompose. Cariaso (1983) has estimated that a 1 ha pen could consume as many as 2000 bamboos and 100 "anahaw" palms, with an estimated weight of 600 (60?) tonnes (Cariaso, pers. comm.). However, the quantity of materials used per unit area decreases with increasing pen size. Provisional estimates of the wood used by the fish pens and stationary cages in Laguna de Bay are enormous, although the nature and impact of these materials on the environment is still being assessed.

3.4 DISCUSSION

As argued in Sections 3.2 and 3.3 above, water-based culture systems (pens and cages) differ from land-based systems (silos, ponds, raceways, recycle systems) in two important ways. In contrast to land-based production systems which are usually built on privately owned or rented land, cages and pens utilise lakes, reservoirs and rivers which for the most part are state owned. By definition these waters are publicly owned and should be managed for the benefit of the public. They can be used to generate hydro-power, as a supply of water for drinking, irrigation or industrial purposes, for fishing and for recreation. Many rural communities have developed around inland water bodies and depend on them

for their livelihood. Thus their large-scale use for fish culture by privately owned fish farms will, unless carefully managed, lead to conflict of interests. Pen culture can cause more friction than cage culture, since pens are much larger and are usually owned by single persons or corporations, thus limiting the number of beneficiaries at a site. Because of the high investment necessary for construction outsiders are often involved, thus aggravating tensions.

Secondly, cage and pen culture systems are much more open than land based systems, and must be considered as subcomponents of the lake/river/reservoir watershed ecosystem in which they operate. Interactions between the environment inside and the environment outside the enclosure occur with little restriction, and so changes in one part of the ecosystem inevitably have an effect on all other parts, to a greater or lesser degree.

The impacts of cage and pen culture are summarised in Figs. 12 and 13. Common to extensive, semi-intensive and intensive methods are the effects of the enclosures themselves on water flow, currents and sediment transport, and on space and aesthetics. In most situations, the most important of these impacts will be on space.

The siting of cages and pens within a water body and with respect to each other is of great importance, since the enclosed fish depend on water flow through the enclosures for food and/or O_2, and to remove toxic metabolites (Schmittou, 1969; Awang Kechik et al, 1983). However, it seems that at least for extensive and semi-intensive operations, the optimum siting of enclosures within a water body is likely to maximise interference with other users, since the cages and pens should be widely dispersed (see Section 4.6 below). From the point of view of fishermen and other users, it would be best to restrict enclosures to particular areas and therefore in such multi-use water bodies there must inevitably be a compromise between parties.

Also common to all methods of cage and pen culture are the effects of enclosing large numbers of fish on local fauna - predatory birds and mammals, wild fish and especially parasites and other disease organisms. However, from both published accounts and from discussions with fish farmers and experts it must be concluded that such impacts are much less important in tropical freshwaters. For example, disease outbreaks appear to be almost unknown in warmwater cage and pen fish culture, unlike the mass mortalities which occur from time to time in temperate salmonid farms. One reason may be the paucity of data, especially from the tropics. Nevertheless, there is also some evidence to suggest that several of the more important cultured tropical fishes such as the tilapias, may be 'tougher' than the temperate salmonids and catfishes i.e. although tilapias may frequently harbour a range of potentially pathogenic organisms these rarely cause widespread mortalities. These apparent differences in disease resistance may in part be due to differences in culture methods. In Europe and North America intensive methods, associated with high stocking densities, are practiced in contrast to the usually less heavily stocked extensively and semi-intensively reared tropical fishes. Thus the methods practiced in temperate countries may be more stressful to the fish, resulting in suppression of the immune system, and increased susceptibility to infection (Wedemeyer, 1970; Snieszko, 1974; Roberts, 1979).

However, all evidence to date suggests that the method of culture has the greatest impact on the environment, since it directly affects nutrient concentrations, O_2 levels, and concentrations of toxic metabolites (Eley et al, 1972; Penczak et al, 1982; Phillips et al, 1983) (Figs. 11 & 12). Disease organisms thrive in eutrophic conditions (Numann, 1972; Grimaldi et al, 1973; Lundborg and Lyndberg, 1977) and changes in water quality have also been shown to affect the amenity value of water for drinking purposes (Jones and Lee, 1982; Beveridge and Muir, 1982) recreation (Vaughn et al, 1982) fish production and fisheries (Henderson et al, 1973; Melack, 1976; Liang et al, 1981) and pressure from these interests may in turn curtail or restrict enclosure culture, as has happened in Laguna de Bay in the Philippines and Loch Lomond in Scotland. Negative feedback of changes in water quality on enclosure fish production have also been demonstrated (Aquino, 1982; Kitabatake, 1982).

In order to maximise fish culture potential, or calculate the relative costs and benefits of fish culture in a multiuse water body, the impact of extensive semi-intensive and intensive cage and pen culture must be quantified in water quality terms. Lack of this information has forced various agencies in both temperate and tropical countries to set development limits which, because they have been based on few data, have been viewed as somewhat arbitrary. This angers both fish farmers and opposing interests, and has resulted in several instances in their flagrant disregard.

Chapter 4

MODELLING OF ENVIRONMENTAL IMPACT

4.1 INTRODUCTION

Water bodies may be classified on a scale ranging from unproductive to productive, depending on the rate of biomass production (Welch, 1980; Forsberg and Ryding, 1980). Various indices such as primary production (Grandberg, 1973), algal biomass (Dillon and Rigler, 1974), oxygen deficit (Cornett and Rigler, 1979; Welch, 1980), indicator species (Rawson, 1956), fish yield (Melack, 1976; Oglesby, 1977) aquatic macrophyte production (Canfield et al, 1983) and nutrient concentration (Vollenweider, 1976), or combination of the above (Carlson, 1977) can be used to assess productivity. However, all reflect and are related to changes in nutrient supply (see below).

The introduction of enclosure culture to a water body will alter the productivity, and although cage and pen culture can influence the flora and fauna directly through the introduction of novel species (parasites, exotic fishes etc) and the attraction of predatory birds and mammals to the area, most of the changes that occur are as a result of changes induced in the productivity. The direction of change is determined by the method of culture employed (extensive/semi-intensive/intensive), whereas the magnitude of the changes will depend upon the characteristics of the site, the type of enclosure structure used, the species cultured and the size of the venture. These relationships are summarised in Fig. 13.

In Fig. 14, the impact of enclosure culture is seen to range from a net uptake of nutrients, resulting in a decrease in productivity, to a net output of nutrients, resulting in an increase in productivity. Extensive culture relies on natural food, and therefore by stocking, culturing and harvesting fish, nutrients are removed from the system. During intensive culture all nutritional requirements are met through the external supply of high quality food, and thus there is a net increase in supply of nutrients to the system through waste feeds, faeces and urine. The slope of the line, and the points at which it intercepts the X and Y axes depend on a number of variables: species, site, season, stocking density, quality of food, management. At the point where the line crosses the X-axis, there is effectively no change in productivity and the quantity of supplementary feed used balances the impact of the fish culture operation.

In attempting to model how the environment changes when cage and pen culture methods are used, we need to know:-

(i) What determines the trophic state of the environment
(ii) What the cultured fish produce/consume in terms of wastes/food
(iii) How the environment responds to these changes

We also require to know how much change is permissible in order to try to manage the system.

4.2 TROPHIC STATE AND PRODUCTIVITY

Aquatic ecosystems consist of large numbers of different types of organisms which depend upon the fixation of light into carbon-containing compounds by photosynthetic green plants, and the subsequent cycling of material through a complex web of food chains (Barnes, 1980). Most lakes and reservoirs derive their energy base of organic material principally from autochthonous (internal) production by algae, macrophytes and periphyton (Pomeroy, 1980). These plants require only light, a carbon source and a supply of nutrients. Plant material is consumed by planktivores and herbivores which in turn are preyed on by primary and secondary carnivores. Unconsumed plant and animal material plus faecal material form the non-living organic detritus which is utilised by a wide variety of organisms - suspension feeders, shredders, grazers, scrapers, deposit feeders and bacteria and fungi.

In some lakes and reservoirs fringed by swamps, such as Lake Chilwa in Africa and Bukit Merah in Malaysia, and in many lotic systems, the external supply of dead organic material (allochthonous) may be greater than autochonous tissue elaboration by macrophytes and algae (Cummins, 1974; Howard-Williams and Lenton, 1975; Townsend, 1980; Yap, 1982, 1983) (see also 2.2 above). Productivity data from a range of deep and shallow water bodies (reservoirs, lakes, rivers) from throughout the world are summarised in Fig. 15. The data comes principally from the IBP results (Le Cren and Lowe-McConnell, 1980), but also includes more recent data from tropical South America, Africa, and the Philippines (Hill and Rai, 1982; Marten and Polovina, 1982; Tundisi, 1983). It can be seen that in general there is an increase in gross primary production ($gCm^{-2}day^{-1}$) from high to low latitudes, and this corresponds to the findings of Brylinsky and Mann (1973) Schindler (1978), and Hill and Rai, (1982). Low latitudes have greater solar radiation and higher temperatures than high latitudes, and it is thought that the greater availability of light and the effects of temperature on growth kinetics underlie this trend. These findings are strongly supported by theoretical considerations, and their validity has been subject to much scrutiny in both the laboratory and the field (e.g. Schiff, 1964; Talling, 1957, 1971; Goldman and Carpenter, 1974).

From the IBP global data set a second correlation was found by Brylinsky and Mann (1973), between primary production and nutrient concentration, as measured by conductivity. A range of nutrients are required for growth by algae and macrophytes and these include several vitamins and a large number of inorganic salts (Stewart, 1974; Fogg, 1975, 1980). In theory any one or more of these essential nutrients could restrict growth. If the supply of a particular nutrient was less than the demand of the primary producers then this nutrient would be limiting. The search for which nutrient/nutrients limit primary production in inland waters has been of consuming interest to scientists and resource managers for years. The arguments hinge around the questions of supply and demand.

Although vitamins such as cobalamin, thiamine and biotin/coenzyme R have been identified from laboratory work as essential, they have rarely been found to be limiting under natural conditions (Welch, 1980). Thus research has been focussed on inorganic nutrients. In undisturbed ecosystems most of these nutrients are derived principally from the erosion of rocks and soil (the lithosphere), although C, N, B, S and Cl also have large atmospheric reserves. Recent studies have shown that many of these atmospheric nutrients are never or rarely limiting. The demand

for B, S and Cl is much less than the supply (Moss, 1980). Carbon is the element required in largest quantities for primary production and most appears to be atmospheric in origin (Schindler, 1971, 1974). Although large pools of dissolved organic C compounds such as humic acids are found in some water bodies (e.g. Scottish Highlands), these are highly resistant to chemical oxidation (Shapiro, 1957). However, atmospheric CO_2 is readily dissolved and easily enters aquatic ecosystems through diffusion or in rainwater (Hutchinson, 1957). Current opinion is that although C may be temporarily limiting, for most of the time supply exceeds demand by a factor of about 30 (Schindler, 1971, 1974; Moss, 1980; Welch, 1980).

Nitrogen constitutes almost 80% of the atmosphere, but despite this is relatively unreactive. Before it becomes available to plants, atmospheric N must be fixed either through electrical discharge (lightning) or through biological fixation by bacteria and blue-green algae. The relative importance of N-fixation to the total annual input of N to a water body varies greatly, from $<1\%$ in Lake Windermere, England, (Horne and Fogg, 1970) to almost 90% in Pyramid Lake, Nevada, USA, (Horne and Galant, in Goldman and Horne, 1983), and is primarily dependent on the density of blue-green algae. Other sources of N include rainwater, which contains both NH_4 and NO_3, although the relative amounts of each fraction differ between temperate and tropical areas (Hutchinson, 1957).

In the absence of O_2, bacteria can denitrify NO_3 to N_2, which then may be lost to the atmosphere. However, this process is now thought to be of little importance in N-limitation (Welch, 1980). Nevertheless, there is evidence that N can be limiting to growth in a number of circumstances, and these will be discussed below.

Of those essential elements derived almost solely from the lithosphere, P is the scarcest with respect to algal and higher plant requirements (Vallentyne, 1974). In Table 8, the relative amounts of the other essential elements in the lithosphere compared to P are shown in column 2. Those elements with a ratio of <1 are less common than P, and include Mn, Co, Cu, Pb and Mo. The third column shows the ratio of P to algal and higher plant requirements. Values >1 show those elements which are in greater demand than P (e.g. Ca, K, Mg). In column 4, the ratio of supply (column 2) to demand (column 3) is shown. Values >1 show those elements whose demands are more likely to be met by lithosphere supply than those of P, and it can be seen that all elements fall into this category.

The reasons for the scarcity of P are threefold. First of all, it is relatively rare, there being no gaseous reserves in the atmosphere (unlike C, H or N), and secondly it is relatively insoluble and readily complexes with a wide range of metals which includes Fe, Al, Mn and Ca, and is thus precipitated (Stumm and Leckie, 1971). Phosphorus also adsorbs on the surface of particulate organic matter and is absorbed by phytoplankton, both of which being comparatively heavy are prone to sedimentation and loss from the water column (Welch, 1980; Sonzogni et al, 1982).

On theoretical grounds, therefore, P and N are prime contenders as limiting nutrients. Algal requirements for N are about 16 times greater than for P, on a molecular basis, as calculated by Stumm (1963) (in Welch, 1980)

$106CO_2 + 90\ H_2O + 16NO_3 + 1PO_4 + \text{Light} \quad C_6H_{180}O_{45}N_{16}P_1 + 154\frac{1}{2}O_2$

Results from experiments by Chiandani and Vighi (1974) confirm this and show the range of algal N:P requirements to be 17-13:1 (8-6:1 on a weight:weight basis). Similar conclusions were reached by Palaheimo and Zimmerman (1983). However, the results from fertilisation experiments, where N, P, C, and trace metals have been added to lakes and reservoirs in various combinations and subsequent changes in productivity measured (Goldman, 1960; Schindler, 1971, 1974; Schindler and Fee, 1974; Robarts and Southall, 1977) have demonstrated that additions of N have little or no effect whereas even small amounts of P can stimulate production dramatically. Additions of C and trace metals have also been found to have limited effect.

Indirect evidence from analyses of large data sets compiled by a number of government bodies and researchers on productivity, plankton biomass and nutrient levels in lakes and reservoirs has confirmed that P is usually the limiting nutrient. These data are summarised in Table 9. First of all, almost all of the lakes investigated have N:P ratios above the critical 8:1 value, suggesting that there is adequate N available to supply algal requirements. Exceptions have been found in P-rich volcanic areas, such as in areas of Japan (Sakamoto, 1966), East and Central Africa (Moss, 1980) and South Island, New Zealand (White et al, 1982). Secondly, although weak correlations between plankton biomass and total N exist (e.g. OECD, 1982; Prepas and Trew, 1983; Hoyer and Jones, 1983), much stronger correlations are found with spring or summer total-P concentrations.

Most of these regressions have a considerable amount of variance associated with them, and some data sets show weaker total P-algal biomass (as measured by chlorophyll 'a' concentrations) correlations than others e.g. North American reservoir data of Canfield and Bachmann (1981), Jones and Novack (1981), and Walker (1982). Part of the variance may be explained by differences in methodology (Hoyer and Jones, 1983), and by inter- and intra-specific differences in algal chlorophyll 'a' content (Palaheimo and Zimmerman, 1983). Not only does the chlorophyll 'a' content vary from one species to another, but it also changes with age, cell volume, light intensity and nutrient concentration (Nicholls and Dillon, 1978; Grandberg and Harjula, 1982). Using multiple regresson techniques, N has been found to account for little or none of the variance in all but one data set (Clasen, 1981; Walker, 1982; OECD, 1982; Prepas and Trew, 1983; Hoyer and Jones, 1983), confirming that total N:P ratios are usually above the 8:1 level, and that few water bodies contain ideal N:P ratios for algal growth.

However, multiple regression analyses have identified one further important factor which can account for a large part of the variance in some instances: turbidity. Generally, water clarity, as measured by secchi disc, is a function of algal density (Bachmannand Jones, 1974; Dillon and Rigler, 1975). However, analyses of a large number of North American lakes and reservoirs by Canfield and Bachmann (1981) have shown this relationship to be weaker in artificial lakes, which often have high levels of inorganic suspended solids. Other recent studies have shown that algal biomass - total P relationships in shallow water bodies which are susceptible to wind-induced disturbance of bottom sediments and in those with high inputs of inorganic nutrients are weak (Pieterse and Toerien, 1978; Clasen, 1981; Nielsen, 1981; Walker, 1982; Hoyer and Jones, 1983). Inorganic suspended solids can reduce plankton biomass and adversely affect production in several ways. High inorganic turbidities

reduce light penetration and restrict the depth of the euphotic zone (Marzolf and Osborne, 1972; Moss, 1980; Canfield and Bachman, 1981), and a number of studies have also shown that PO_4-P is readily adsorbed onto inorganic particles thus decreasing the concentration of biologically available P (Fitzgerald, 1970; Stumm and Leckie, 1971; Edzwald et al, 1976; Furness and Breen, 1978; Hoyer and Jones, 1983).

Phosphate-P concentration is currently regarded as the primary limiting factor governing algal biomass and productivity for large parts of the year in both temperate and tropical inland waters. However, the generalised P-algal biomass relationships tend to treat all water bodies as a homogenous group despite the fact that the P-algal biomass/primary production correlations in Table 9 suggest that there is often a great deal of associated variance that can only be explained by taking into account other locally important factors such as geology, depth, exposure, climate and watershed size and use. As more empirical data is collected, refined models governing different categories of water body will evolve.

In summary, aquatic food chains function as shown in Fig. 15. In lentic water bodies, autochthonous production of organic material and its subsequent processing, fuels the system. In lotic water bodies, particularly fast-flowing erosive systems, plankton are often present in insignificant numbers and the main sources of energy are derived from periphyton, fringing macrophyte communities, or allochthonous detrital material. Productivity of the entire system may be controlled at any of the points illustrated in Fig. 15:- light, essential nutrients or, in the case of lotic systems, allochthonous detritus.

4.3 THE CARRYING CAPACITY OF INLAND WATERS USED FOR INTENSIVE ENCLOSURE CULTURE

4.3.1 Phosphorus and fish diet

Phosphorus and, occasionally, light are the principal factors limiting production in both temperate and tropical freshwaters, and thus the net addition or uptake of P or materials which greatly influence the light climate will alter productivity. In this Section, however, the latter factor will be ignored but will be considered in Section 4.6.

Phosphorus is an essential element required by all fish for normal growth and bone development, maintenance of acid-base regulation, and lipid and carbohydrate metabolism (Ketola, 1975; Ogino and Takeda, 1976; Lovell, 1978; Cowey and Sargent, 1979; Lall, 1979; Sakamoto and Yone, 1980; Takeuchi and Nakazoe, 1981). Diets deficient in P can suppress appetite, normal food conversion and growth, and under extreme circumstances affect bone formation and lead to death (Murakami, 1967; Andrews et al, 1973; Lall, 1979). Although the uptake of labelled ^{32}P by fish from water has been demonstrated many times (e.g. Tomiyama et al, 1956, in Lall, 1979), it is believed that the rate of absorbtion is generally very low, and that fish derive their P requirements principally from food (Phillips et al, 1957; Nose and Arai, 1979).

Phosphorus requirements for different species of fish range from 0.29% to 0.90% of the diet (Table 10). However, these figures refer to available phosphorus which varies greatly with species depending on the dietary source. The majority of currently available intensive fish feeds

are largely of animal origin, such as fish meal, meat meal and bone meal, where most of the P is present in inorganic form, and the remainder is in the form of P-complexes in proteins, lipids and carbohydrates (Lall, 1979). Nearly all of this P is readily available to carnivorous fishes such as rainbow trout (Ogino et al, 1979). However, the availability of P in fish meal diets to omnivores and herbivores is highly variable. Whilst O. niloticus can utilise 65% (as much as rainbow trout) of P in fish meal based diets (Watanabe et al, 1980a), the availability to common carp is almost zero (Ogino et al, 1979) due to the absence of acidic gastric juices (pepsins) (Yone and Toshima, 1979). On the other hand, 60-80% of the total P in plant materials exists as the Ca or Mg salt of phytic acid, known as phytin, and is unavailable to fish as they don't possess the necessary enzyme, phytase, to break down the compound. (Ogino et al, 1979; Lall, 1979). There is some evidence that omnivores/herbivores such as the carps are better at utilising the non-phytin fraction in plant-based diets than the carnivorous rainbow trout (Ogino and Takeda, 1976).

The availability and utilisation of P has also been shown to be influenced by the amount ingested, body P reserves, other elements in the gut and body tissues, and the remaining dietary ingredients (Nakamura, 1982; Tacon and De Silva, 1983). Thus, depending on the digestibility of the source, a significant proportion of the P intake may be egested. Absorbtion efficiency and (at levels above dietary requirements) growth rate, however, are independent of the level of dietary P, and hence excretion is positively related to intake (Nakashima and Leggett, 1980). Phosphorus surplus to dietary requirements is largely excreted through the kidneys (Forster and Goldstein, 1969). These relationships between intake, excretion, growth and absorbtion efficiency are illustrated in Fig. 16.

Most feeds used for intensive culture in temperate countries are commercially made and are in dry, pelleted form. Some farms in Europe still use trash fish as a diet, although this practice is now being restricted in many countries (see Alabaster, 1982a). A summary of Tacon and De Silva's (1983) survey of the P content of commercially available European salmonid diets is given in Table 11. Mean values suggest that P content of trout diets is $\sim$ 1.49%, and that of salmon $\sim$ 1.47%. In Poland, Penczak et al (1982) used feeds (dry pellet, and fresh fish/wheat bran/yeast moist pellets) with an average P content of 1.45%, for cage culture of trout, whilst Ketola (1982) in the USA used a European "low-pollution" diet (1.40%) and a commercially available North American diet (2.2%) in his trout culture studies.

Intensive culture of carps and tilapias still relies largely on the manufacture of diets from locally available materials, the exception being the commercially produced tilapia diets available in Taiwan. The P content of raw materials and diets in use in various countries is given in Table 12. For tilapias, the P content of diets varies between 1.30 and 2.52%, whilst those compounded for carps vary between 0.93 and 3.06%.

Feed losses are inevitable during fish culture for a number of reasons. Many near-surface feeding fishes, such as the salmonids, are visual feeders (Blaxter, 1980) and only ingest food items within a particular size range which is positively related to some function of fish biomass (Wankowski and Thorpe, 1978). Pellet sizes for salmonids, based on manufacturers' recommendations, are given in Table 13. Food items which are outside the particular recommended size category for a given size range of trout, will not be eaten, but instead contribute to the wastes from the operation. Manufacturers estimate that 2% of feed is

'dust', due largely to the crumbling of pellets during packing and transport. Thus at least 2% of commercial trout feeds will be uneaten.

Particle size in the diet of tilapias seems at first glance to be less important. Many of the cultured species, such as O. niloticus and O. aureus are microphagous feeders (Bowen, 1982), and according to Miller (1979) and Coche and Lovshin (Pullin and Lowe-McConnell, 1982) powdered feeds produce as high yields from pond culture as pelleted feeds, without the added expense of pelleting.

Whilst the above findings may apply to tilapia culture in ponds and pens, they do not apply to cage culture. Losses of feed from cages have frequently been observed (Collins, 1971; Loyacano and Smith, 1976; Hoelzl and Vens Cappell, 1980; Penczak et al, 1982; Phillips et al, 1983), and are due both to passive water currents as well as to currents induced by the fish during feeding. Thus pelleted feeds for tilapia cage culture have been recommended by many authors (Guerrero, 1980; Coche, 1982; Santiago, 1983). Jauncey and Ross (1982) have observed that in general tilapias prefer smaller pellet sizes than most other cultured species, and recommended sizes are given in Table 13.

In summary, P is an essential mineral which fish obtain almost exclusively from their diet. Most diets developed for intensive culture contain P surplus to requirements or in a form which is partially unavailable to the fish. Surplus P is excreted, whilst unavailable P is passed out in the faeces. In fishes such as the salmonids which have size-specific preferences for food, damaged pellets may not be ingested, but instead contribute to the P supply of the water body. Other sources of P to the environment are derived from food which is washed out of the cage by both natural currents and turbulence caused by the fishes during feeding.

4.3.2 Quantification of P losses

The principal P losses to the environment associated with intensive enclosure culture are summarised in Fig. 17. There are several methods which can be used to quantify these losses:-

(i) Direct measurement of inputs from pens and cages

(ii) Theoretical calculations based on available information on P content of feeds, etc.

(iii) Extrapolation of data from intensive pond and raceway culture to cage and pen production.

Although there are a number of studies where wastes from intensive cage trout farms are being measured (see Section 3.3.2), only that of Penczak et al (1982) has been completed. In this study, waste production from cage trout culture at Glebokie Lake, Poland, was determined by measurement of C, P and N inputs and outputs. Total nutrient losses to the environment, Nut_{env}, were computed as being equivalent to the difference between the nutrients added in the food, Nut_{food}, and those assimilated by the fish which were subsequently harvested, Nut_{fish}:-

$$Nut_{env} = Nut_{food} - Nut_{fish}$$

A combination of trash fish and pellets were used as feeds, and the C, P and N composition, as well as the quantities used were recorded. The weights and C, P and N content of the trout harvested were measured and nutrient loads to the lake computed on a per-kg-cage-fish-production basis.

The results are summarised in Table 14, and show that for every kg of fish harvested, the lake was enriched by 0.75 kg C, 0.023 kg P and 0.10 kg N.

A similar method was used by Beveridge et al (1982), based on published data on P content of feeds, FCR (Food Conversion Ratio) values, and P content of fish carcasses. In Table 16, total-P loads associated with intensive trout and tilapia culture have been calculated, using the feed formulations detailed in Table 12, and their associated FCR values (Table 15). The total-P content of trout and tilapia carcasses is taken from Ogino and Takeda (1978), Penczak et al (1982) and Meske and Manthey (1983).

The total-P load to the environment is variable, depending on the P content and the digestibility of the feed used. For trout, the most common FCR values for cage culture are 1.5-2.0:1, and thus total-P loads per tonne fish produced are 17-25 kg. For intensive tilapia production the usual FCR values are in the range 2.0-2.5:1. The exceptionally high FCR value for the Central African Republic diet is believed to have been due to poor O_2 conditions (see Coche, 1982) and will not be considered here. Thus 23-29 kg total-P are added to the environment for every tonne of cage tilapia production. Total-P losses are therefore approximately the same for both intensive trout and tilapia production.

Estimates of total-P loadings from intensive land-based trout culture systems are given in Table 17. Most of the results are based on national surveys commissioned in European countries by EIFAC, and the enormous variation in the results (11-157 kg P tonne fish produced^{-1}) is due to differences in system (pond/raceway/tank; hatchery/grow-out operation), feeding (floating/sinking; dry/wet; hand-fed/automatic feeders) and management practices (treatment/no treatment, prior to discharge), as well as sampling (daily/weekly/monthly) and analysis of effluents (dissolved/dissolved + particulate; total-P/ortho-P) (see Summary in Alabaster, 1982a). It is thus difficult to compare estimates for cage culture with these data. However, Ketola's (1982) results are based on careful measurements of inputs and outputs from one system, and show that trout fed on a standard, commercially available diet in the USA produce a load of 22.77 kg total-P per tonne production, which is within the range calculated above for cage trout production.

Unfortunately, there have been no similar studies of intensive land-based tilapia culture systems.

In estimating total-P loads from intensive cage culture, the feed fish wastes system has been treated as a black box with information restricted to inputs and outputs. However, no attempts have been made to quantitatively or qualitatively analyse the processes within the system which are involved in waste P-production. This is a necessary step prior

to modelling, as recent reviews have shown that the form of P-wastes determines their impact on the environment (Lee et al, 1980; Sonzogni et al, 1982).

The various sources of P wastes in intensive cage culture are summarised in Fig. 17. Many of the parameters or processes involved can be quantified from empirical data, whilst others can be derived theoretically.

For intensive trout culture, total feed losses (dust and uneaten food) are estimated to be 20%, based on manufacturers' figures for dust (2% of feed) and estimates from various studies of 10-30% uneaten food (Collins, 1971; Hoelzl and Vens Cappell, 1980; Penczak et al, 1982). When FCR values for pond and cage culture are compared (Table 18), those for cage culture are at least 20% greater, thus supporting the argument that feed losses from cages are comparatively high.

Some P is leached from the food prior to ingestion. However, if we assume that feed is ingested within 3 minutes of being given to the fish, and if we assume 'worst possible conditions' (small pellet, high temperatures), then only 1% of the P in the feed would be leached out (Beveridge et al, unpublished data).

Using data from Penczak et al (1982) it seems that only 32% of P ingested (23% of feed given) is assimilated and utilised, the rest being either passed out in the faeces, or excreted in the urine.

4.3.3 Modelling of the aquatic ecosystem response to P loadings from intensive cage and pen culture

4.3.3.1 Choice of model

The response of aquatic ecosystems to increases in P loadings has been the subject of intense debate for a number of years, and a wide spectrum of predictive models has been developed. The models are basically of two types: "dynamic" models, which may be defined as "mathematical representations of the key physical, chemical and biological processes governing algal growth" (Jones and Lee, 1982) or statistical models derived from large-scale surveys of lakes and reservoirs. The choice of appropriate model depends primarily on what it is to be used for, and the quality of the available data (Jørgensen, 1980). As stated in the Introduction, we wish to be able to predict the impact of intensive cage and pen culture on water quality (particularly phytoplankton numbers) so that comprehensive guidelines for the development of the industry can be established which take into account not only the effects of changes in water quality on fish production, but also other uses. The model (or models) must be readily useable without recourse to expensive and time-consuming data collection by highly-trained technicians. A simple model with few variables would therefore seem best.

The dynamic models range in complexity from simple 2 or 3 parameter type to the more complex models, such as CLEANER, developed by Massacheussets Institute of Technology, which has 40 variables. A recent study by Straskraba (1982) has shown that the simple predictive models are

as accurate as the much more complex data-hungry models, since for every additional parameter considered, a further source of error is introduced. However, despite the fact that they give a great deal of insight into how aquatic ecosystems function, at this stage in their development they have been found to have limited predictive capabilities (Jones and Lee, 1982; OECD, 1982). Their development has also been restricted to temperate water bodies.

Statistical models based on empirical data were first described by Vollenweider (1968, 1975, 1976), and later developed by Dillon and Rigler (1974), Kirchner and Dillon (1975) and Jones and Bachman (1976) among others. All attempted to predict P concentrations in lakes and reservoirs through various mass balance equations, and to relate these to trophic state (productivity). These models have been calibrated and tested, verified and modified using a number of data bases: the United States Environmental Protection Agency's National Eutrophication Survey (USEPA 1978); the Organisation for Economic Cooperation and Development's survey of water bodies in 18 North American and European countries (OECD, 1982); the IBP global survey (Le Cren and Lowe-McConnell, 1980); and a survey of Southern Africa's lakes and reservoirs (Thornton and Walmsley, 1982; Walmsley and Thornton, 1984). The information is summarised in Table 19. Based on the predictive abilities of the various models, Dillon and Rigler's (1974) model has been chosen as the best available at the present moment. It has been widely tested using shallow and deep lakes and reservoirs in both temperate and tropical regions, and seems to perform best of all (Mueller, 1982; Thornton and Walmsley, 1982.)

Dillon and Rigler's modification of Vollenweider's original model states that the concentration of total P in a water body, [P], is determined by the P loading, the size of the lake (area, mean depth), the flushing rate (i.e. the fraction of the water volume lost annually through the outflow) and the fraction of P permanently lost to the sediments. At steady state,

$$[P] = \frac{L(1-R)}{\bar{z}\rho}$$

where [P] is in gm^{-3} total P, L is the total P loading in gm^{-2} yr^{-1}, $\bar{z}$ is the mean depth in m, R is the fraction of total P retained by the sediments, and ρ is the flushing rate in volumes per year.

4.3.3.2 Using the model

A step by step approach to using the model has been adopted here.

Step 1: In order to determine the potential of a lake or reservoir for intensive enclosure, the productivity of the water body prior to exploitation must be assessed through measurement of the steady-state total-P concentration, [P]. With the exception of very shallow water bodies, temperate lakes and reservoirs are often stratified for much of the year and only mix twice during spring and autumn when there is little difference in temperature and thus density between surface (epilimnion) and deep (hypolimnion) waters, and when there is sufficient wind energy to induce mixing. During stratification, differences in [P] develop between the epilimnion, where P is utilised by algae, and the hypolimnion, where [P] is determined by sediment/water interactions rather than by the algal community. According to Dillon and Rigler (1974), Vollenweider (1976),

and OECD (1982), the steady state [P] in northern temperate waters is therefore best determined at the time of spring overturn.

By contrast, tropical inland waters are either warm monomictic (mix once per year) or polymictic (cycle frequently) (Ruttner, 1963; Wetzel, 1975; Hill and Rai, 1982), and according to Thornton and Walmsley (1982), [P] should be taken as the measured mean annual total P concentration, $\overline{[P]}$ of surface waters.

Step 2: The development capacity of a lake or reservoir for intensive cage and pen culture is the difference between the productivity of the water body prior to exploitation, and the final desired level of productivity. As stated above, [P] can be used as a productivity indicator. However, it must be decided whether it is then mean annual algal biomass, or the peak annual algal biomass, as measured by chlorophyll levels $\overline{[chl]}$ and $[chl]^{max}$ respectively, that we wish to predict. Since fish are usually held in cages throughout the year, it is the latter parameter which should be considered.

The desired peak algal biomass is determined by a number of criteria, the most important being whether the water body is multi-purpose or single purpose (i.e. for fish culture alone). The multi-purpose nature of inland waters is impaired with increasing productivity - particularly if already highly productive (OECD, 1982) - and thus limits should be carefully set. However, it is difficult to find hard and fast guidelines as to recommended levels, since water resources vary in quantity and quality from country to country. For example, water used for drinking purposes should be as clean (i.e. free from toxic or noxious substances) as possible, and this is easiest to achieve when unproductive, unpolluted sources are used. However, in areas of high soil fertility highly productive water bodies may dominate and may have to be used for domestic supplies.

Recommended acceptable ranges and maximum permissible values of $\overline{[P]}$ for water bodies with different uses are suggested in Figure 18 and Table 20. The [P] (mg m^{-3}) values can be related to both $[chl]^{max}$ (mg m^{-3}) and $\overline{[chl]}$ (mg m^{-3}), using the correlations derived by OECD (OECD, 1982) for temperate waters, and these relationships are summarised in Table 21. Note that three equations relate both $\overline{[chl]}$ and $\overline{[P]}$ and $[chl]^{max}$ and $\overline{[P]}$, and that two equations relate to [chl] and $[chl]^{max}$. The size of the data base used also varies. The first equation in each case utilises unscreened data. However, for the second equation data from lakes where light is the limiting factor, due to heavy natural silt loads, and from lakes where artificial aeration is used, are omitted. In all cases, the correlation, r, is improved. The third equation uses data which has been further screened, and from which lakes where N might be a limiting factor (i.e. N:P ratios < 10) are not included, and this further improves correlations. Annual gross primary production ΣPP (gC m^{-2} yr^{-1}) is related to both [P] and to algal biomass by linear equations:-

$$\Sigma PP = 31.1[\overline{P}]^{0.54}; \quad r = 0.71; \quad S.E. = 0.265; \quad n = 49$$

$$\Sigma PP = 56.5[\overline{chl}]^{0.61}; \quad r = 0.79; \quad S.E. = 0.242; \quad n = 49,$$

despite evidence of self shading and thus reduced algal biomass levels at high [P] (OECD, 1982).

Unfortunately, there are few data relating [P], algal biomass and productivity in tropical waters. However, in a recent paper Walmsley and Thornton (1984, in press) show that most southern African impoundments exhibit similar relationships to the North American and European OECD study lakes and reservoirs between [chl], [P] and orthophosphate $[P]_0$:-

$$[\overline{chl}] = 2.06[\overline{P}]_0^{0.387} \quad r = 0.81; \quad n = 29$$

$$[\overline{chl}] = 0.416[\overline{P}]^{0.675} \quad r = 0.84; \quad n = 16$$

According to Melack (1979), three temporal patterns of algal biomass and productivity exist in the tropics. Most water bodies show pronounced seasonal fluctuations corresponding to variations in rainfall, river discharges or mixing. Yet other water bodies exhibit little seasonal variation, whilst a third category shows periodic abrupt changes from one persistent (>10 generations) species assemblage and level of photosynthetic activity to another persistent condition. However, there are insufficient data to relate $[\overline{chl}^{max}]$ to either [P] or $[\overline{chl}]$.

The few available data relating $[\overline{chl}]$ to mean photosynthetic rate are summarised in Table 22, although due to the paucity of data and the range of units used, no relationship could be derived.

Step 3: The capacity of a water body for intensive cage and pen fish culture is the difference, $\Delta[P]$, between [P] prior to exploitation, $[P]_i$, and the desired/acceptable [P] once fish culture is established, $[P]_f$.

$$\text{i.e. } \Delta[P] = [P]_f - [P]_i$$

$\Delta[P]$ is related to P loadings from fish enclosures, L_{fish}, the size of the lake, A, its flushing rate, ρ, and the ability of the water body to handle the loadings (i.e. the fraction of L_{fish} retained by the sediments, R_{fish}):-

$$\Delta[P] \quad \frac{L_{fish}\ (1-R_{fish})}{\bar{z}\rho}$$

$$L_{fish} = \frac{\Delta[P]\bar{z}\rho}{1-R_{fish}}$$

The acceptable/desirable change in [P], Δ[P] (mg m^{-3}), is determined as described above, and $\bar{z}$ can be calculated from hydrographic data obtained either from literature or survey work:-

$\bar{z} = \frac{V}{\bar{A}}$ where V = volume of water body (m^3) and A = surface area (m^2) the flushing rate, (y^{-1}) is equal to Q_o/V, where Q_o is the average total volume outflowing each year. Q_o can be calculated by direct measurement of outflows, or in some circumstances can be determined from published data on total long-term average inflows from catchment area surface runoff (Ad.r), precipitation (Pr) and evaporation (Ev), such that

Q_o = Ad.r + A(Pr - Ev) (see Dillon and Rigler, 1975, for further details).

The retention coefficient, R, can be determined experimentally by measuring the mean annual inflow and outflow [P], $[\bar{P}]_i$; and $[\bar{P}]_o$ respectively:-

$$R = 1 - \frac{[\bar{P}]_o}{[\bar{P}]_i}$$

Using multiple regression analysis of data from temperate water bodies, Kirchner and Dillon (1975) found R to be highly correlated to the annual hydraulic loading, Q/A, such that:-

$$R = 0.426 \exp(-0.271\,{}^{Q}/_{A}) + 0.574 \exp(0.00949\,{}^{Q}/_{A}),\ r = 0.94,$$

where Q = annual hydraulic loading (m^3). Various other models have been developed for specific types of water body, such as oligotrophic or fast-flushing temperate lakes (Larsen and Mercier, 1976; Ostrofsky, 1978) and many of these have been critically evaluated by Canfield and Bachmann (1981). In view of their conclusions, it seems best to use different computations for R, depending on the type of water body being assessed, although of course choice will also depend on available information. Models are summarised in Table 23.

A similar, though less precisely defined relationship between R and ${}^{Q}/_{A}$ seems to hold for tropical lakes and reservoirs (Thornton and Walmsley, 1982) (Fig. 19). However, until the data necessary to define the relationship have been collected, temperate models must be used.

L_{fish} is largely in particulate form, and the proportion of the waste faecal and food P which contributes to the pool of dissolved P depends on many factors; the P content of the feed, diet composition, pellet shape, temperature, depth of water under the cages, presence/absence of scavenging fish, etc. (Bienfang, 1980; Collins, 1983; Merican, 1983). Modelling of these wastes is in progress, and preliminary data suggests that $R_{fish} > R$. However, until such models are available, R_{fish} must be assumed to be the same as R in the first instance, and, subsequent to the introduction of cages and the steady state [P] having been reached (see below) it must be recalibrated:-

$$R_{fish} = R\left(\frac{[P]\ obs}{[P]\ exp}\right)$$

The response time of a water body to increases in P loading is a non-linear function of the water residence time, $t(M)[t(M) = 1/\rho]$, and mean depth, $\bar{z}$. The expected 95% response time, $t(M)_{95}$, which is used as an approximation to the full response time, can be calculated from Fig. 20.

Step 4: Once the permissible/acceptable total P loading, L_{fish}, has been calculated, then the intensive cage fish production (tonnes y^{-1}) can be estimated by dividing L_{fish} by the average total P wastes per tonne fish production (Table 16). A worked example is given in Appendix 1.

4.4 THE CARRYING CAPACITY OF INLAND WATERS USED FOR EXTENSIVE ENCLOSURE CULTURE

4.4.1 Introduction

Before considering how to model the impact of extensive cage fish culture on the environment, the rationale behind using this method to increase fish production must be examined.

As discussed in Section 4.2, the rate of primary production in inland waters is dependent upon the availability of essential nutrients and light. Production in all other communities within the ecosystem is to some extent dependent upon primary production, and thus it is not surprising that Σ PP and annual fish yields, Fy, are related (Hrbacek, 1969; Henderson et al, 1973; Melack, 1976; Oglesby, 1977, 1982; McConnell et al, 1977; Hecky et al, 1981; Marten and Polovina, 1982; Adams et al, 1983).

Information on fish yields and productivity in tropical lakes and reservoirs are summarised in Fig. 21. The line which best fits the data is curvilinear, of the form $Y = Ae^{Bx}$, and the correlation coefficient, r, is 0.64. There is a large amount of scatter in the data, which accounts for the low correlation value, and much of this variance is undoubtedly due to how the data were collected. However, there are several additional factors which must be considered. First of all we don't know the relative importance of other autochthonous sources of energy, such as periphyton or macrophytes, or the allochthonous inputs to the water bodies concerned. Both macrophytes and periphyton can make significant contributions to the total energy fixed in lentic water bodies (Moss, 1980), and although allochthonous inputs seem to be relatively unimportant in most lentic water bodies (Adams et al, 1983), they can be important in the energy budgets of small aquatic systems with low retention times, or those surrounded by swamps (Oglesby, 1977). In Bukit Merah reservoir, Malaysia, for example, more than 90% of the C cycled through the system is derived from allochthonous sources (Yap, 1983) thus leading to high production of detrivorous fishes and higher than expected yields per unit primary production.

Secondly, we don't know at what intensity the fisheries are being managed, or what gears are being used. A lightly exploited fishery (i.e. one operating well below maximum sustainable yield) would give low yields per unit primary production (Marten and Polovina, 1982). Finally, this plot does not take into account the types of fish being harvested.

The general shape of the curve is interesting, and suggests that at low levels of primary production, trophic transfer efficiences (production at tropic level 1/production at trophic level n-1) are low, whilst in highly productive water bodies transfer efficiencies are much higher. However, this is likely to be an artefact of the data pool used. Not only must the data vary qualitatively in terms of how primary production and fish yields were estimated, but also few highly productive water bodies were included in the analysis. Liang et al (1981) suggest that in fact the relationship is sigmoid, and that the data used here relates only to the lower portion of the curve. It is thus suggested that trophic transfer efficiencies are lower in highly productive waters.

On theoretical grounds, Slobodkin (1960) and others have suggested that ecosystem trophic transfer efficiencies should be around 10-15%. However, comparatively low transfer efficiencies of between 4 and 10% are common in freshwaters (Wright, 1958; Gulati, 1975; Rey and Capblancq, 1975; Coveney et al, 1975; Lewis, 1979). The efficiency of herbivore grazing is in part dependent upon phytoplankton quality - size, species, etc. (Zaret, 1980). However, in many instances the herbivorous zooplankton populations are heavily suppressed by predation, thus accounting for their failure to crop the major portion of primary production (Rigler et al, 1974; Jassby and Goldman, 1974; Kalff et al, 1975; Coveney et al, 1977; Lewis, 1979). Although there is a positive relationship between zooplankton and phytoplankton biomass, the ratio decreases with increasing productivity (McCauley and Kalff, 1981). Recent studies of zooplankton populations in temperate and sub-tropical lakes show that as productivity increases, zooplankton community composition shifts to dominance by microzooplankton (cilicates, rotifers, nauplii) which feed principally on bacteria (Gannon and Stemberger, 1978; Bays and Crisman, 1983). Thus in highly productive systems relatively more of the carbon fixed is diverted to the detrital pathways (Gliwicz, 1969; Pedersen et al, 1976; Wissmar and Wetzel, 1978), and by comparing observed with expected transfer efficiencies, it seems that as little as 30% of the phytoplankton production in lentic water bodies is grazed by herbivores.

By increasing grazing pressure through the stocking of microphyte-feeding fishes, part of the detrital supply could be converted directly into fish production, thus avoiding the energy losses associated with long food chains. Although fishes such as the tilapias and carps which feed at the base of the aquatic food web may have low transfer efficiencies when compared with organisms feeding at higher trophic levels (Borgmann, 1982), nevertheless at each successive step along the food web there are energy losses, so that fisheries which concentrate on capturing fishes at the end of long food chains have comparatively low yields (Jones, 1982).

An increase in herbivore grazing pressure will tend to reduce the average size of individual phytoplankters, whilst causing an increase in the turnover rate (Cooper, 1973) or relative production as it is generally called (Production/Biomass = P/B). Within limits this will stimulate the overall productivity of the system (Opuszynski, 1980).

A further reason for stocking inland water bodies with fishes is that in many tropical freshwaters, particularly in Asia and South America, not all trophic levels may be utilised (Fernando and Holcik, 1982). In such systems where cichlids or clupeids have not been introduced, the fish communities are of riverine origin and are not well adapted to the lacustrine areas of lakes and reservoirs.

The reasons for manipulating aquatic ecosystems through extensive aquaculture (fisheries, ranching, cage and pen culture) are summarised in Figure 22. By stocking with the appropriate species of fish which feed at the base of the food web, vacant niches in the system may be utilised and phytoplankton grazing encouraged, thus increasing the phytoplankton P/B, and reducing energy losses between autochthonous energy inputs and fish yields. Possible adverse effects will be considered in the discussion.

4.4.2 Species and diet

The principal species used in extensive enclosure culture are the tilapias (O. niloticus, O. mossambicus), although carps (H. molitrix, A. nobilis) and milkfish are also grown in this manner in some countries. Cages are more commonly used than pens. Since little research has yet been carried out into the diets of these fishes under extensive enclosure conditions, data from studies of food consumption under natural conditions and in fish ponds, and results from nutritional studies must be used to determine what foods are likely to be consumed, and the relationship between food intake and fish production.

The diets of the tilapias and carps are summarised in Table 24. O. niloticus like all other tilapias is principally a herbivore (Jauncey and Ross, 1982) and its diet under natural conditions is largely restricted to phytoplankton (Moriarty, 1973, Moriarty and Moriarty, 1973, 1973a). However, in highly stocked organically fertilised ponds, where the principal flow of energy is through the detritus pathways and where intraspecific competition for food can be severe, O. niloticus feeds and grows well on organic manures (Wohlfarth & Schroeder, 1979), although the principal nutritive value is not derived from the detritus itself, but from the micro-organisms which cover the surface of the particles (Kerns and Roelofs, 1977; Schroeder, 1978). O. mossambicus is more omnivorous, and it has been found to ingest a wide range of plant materials, as well as zooplankton, fish larvae and eggs, and detritus (Bowen, 1982). However, in cage conditions both species probably feed largely on phytoplankton, supplemented by detritus.

Studies on the diets of caged carps show that silver carp feed primarily on phytoplankton (8-100 um), whilst bighead carp consume phytoplankton, zooplankton and detritus in the range 17-3000 um (Cremer and Smitherman, 1980).

In the following Section, which deals with the potential production from extensive culture, most of the emphasis will be placed on cage tilapia culture which is the most common form of extensive culture. The use of pens and the culture of carps will be discussed in Section 4.6.

4.4.3 The theoretical potential of fish production from extensive culture methods

The food consumption of fishes can be summarised in the following equation:- $C = P + R + F + U$, where C = food consumption in energy terms (joules); P = energy used for tissue growth (including fat deposition, egg and sperm development); R = energy used for work (including body

maintenance, digestion, activity); F and U = energy losses in faeces and urine respectively (Klekowski and Duncan, 1975). The amount of useful energy available to the animal, or assimilation (A) as it is generally termed, can be derived from

$$A = C - (F + U)$$

$$= P + R$$

Assimilation is often quantified in terms of assimilation efficiency (A_e):-

$$A_e = \frac{A}{C} \times 100$$

The A_e values have been found to vary in tilapias, depending on food source and temperature, from 45 to 55% (Table 25).

Many tilapia populations undergo diurnal migrations from the warm littoral regions they inhabit during the day, to the deeper, cooler offshore waters at night (Fryer and Iles, 1972; Bruton and Boltt, 1975; Caulton, 1975). Such behaviour has been shown by Caulton (1978) to have a considerable effect on the A in T. rendalli. At 18°C (average night-time temperature), A_e =~48%, whilst at 30°C (average day-time temperature), A_e = 58%. However, fish held in floating cages are subject to little diurnal temperature fluctuation (± 1-2°C) and thus in a 25°-30°C annual temperature fluctuation we would expect no more than a 5% variation in A (from Caulton, 1982).

Only a portion of the energy assimilated is available for growth. Work done by Caulton (1982) has shown that T. rendalli can utilise approximately 0.5 A for growth, providing it can reduce its metabolic energy requirements by migration to colder waters at night. However, at a constant 28°C, only~ 0.2 A is partitioned into growth, giving an overall food conversion efficiency (energy value of plant tissue consumed/energy value of fish tissue elaboration; P/C) of ~ 10%. O. mossambicus fed on an algal diet, showed a higher food conversion efficiency of 16-22% at 25°C (Mironowa, 1974; in Fischer, 1979), and in the absence of any data, a food conversion efficiency which lies somewhere between the values for other species (15%) has been assumed for O. niloticus reared in cages. (N.B. This value is an estimate and ignores the effects of food quality, age, reproductive condition, etc. Fischer, 1979).

In theory, therefore, 10-15% of primary production could be converted into fish (tilapia) tissue. In Fig. 23, fish production is plotted against primary production. A water body with primary production of 1000g C m^{-2} y^{-1} would yield 1000-1500 g fish tissue m^{-2} y^{-1} or 1000-1500 tonnes km^{-2} y^{-1}, assuming a food conversion efficiency of 10-15%, and a fresh fish carbon content = 10% wet weight (Gulland, 1970). By comparison, the fish yield of a typical tropical inland water fishery with a similar rate of primary production is around 6 tonnes (Fig. 21).

4.4.4 Actual fish yields from extensive aquaculture methods. Stocked fisheries vs. cages.

As discussed above, the difference between actual fish yields, and theoretically possible yields is huge, and there is a great deal of scope for improvement through ecosystem manipulation. According to the classical fisheries theories of Russell (1931) and Beverton and Holt (1957), the size of the exploitable fish stock is determined by four factors - recruitment rate, growth rate, fishing mortality rate and natural mortality rate - which operate as illustrated diagrammatically in Fig. 24. It can be seen that by (i) excluding predators and minimising the effects of disease on the natural mortality rate, by (ii) bypassing the factors that govern recruitment rate, through artificial stocking, by (iii) stimulating the P/B of primary producers and maximising the conversion efficiency of the system through the appropriate choice of species, by (iv) harvesting prior to the food conversion efficiency being adversely affected by age or reproduction, by (v) minimising energy losses through foraging, and by (vi) maximising the fishing mortality rate, fish yields per unit primary production could be maximised.

There are two principal methods by which the above policies can be achieved. Using conventional methods of stocking and fisheries management, it is possible to fulfill criteria (ii) and (iii), and to have a degree of influence on others. The rate of natural mortality can be influenced by an eradication programme of piscivorous birds and mammals (see FAO, 1983, for details of management of Chinese lakes) and by intensification of fishing pressure, which would eliminate losses through age. Increased fishing mortality would increase fish P/B. Fish which cannot breed in lentic systems, such as Chinese carps, could also be stocked, thus minimising the energy losses associated with gonad development, and egg and sperm production. Such management practices are most practicable in small water bodies.

In China, up to 15-fold increases in yields have been achieved through these methods (Tapiador et al, 1977; Liang et al, 1981; FAO, 1983) (Table 26). Assuming 0.04-0.06% average transfer efficiencies from primary production to fish yield prior to stocking (from Fig. 21), this would result in an increase to 0.6 - 0.9%. Transformation of Liang et al's (1981) data for intensively managed lakes near Wuhan, China, shows a range of conversion efficiencies from areal primary production to areal fish yields of 0.5 - 2.3% (gross), or 0.2 - 2.2% (net) (Table 27). However, these figures are probably overestimates, since organic fertilisers and supplementary feeds were used in most of the lakes.

By contrast, most of the criteria for maximisation of yields from primary production can be met using extensive cage culture and consequently, yields should be higher. As an approximation of the conversion efficiencies attainable, data from Almazan and Boyd (1978) for tilapia (O. aureus) yields vs primary production in inorganically fertilised fish ponds has been replotted in Fig. 25. The uppermost curves relate to fish yields assuming 10 and 15% conversion efficiencies, whilst the middle plot is Almazan and Boyd's data. The lowest curve represents fish yields from tropical lakes and reservoirs (Fig. 21 replotted). It can be seen that the tilapia yield curve is of the same form ($Y = Ae^{Bx}$) as that calculated for the tropical lakes and reservoirs, but that the correlation ($r = 0.91$) is much better. For any given value of Σ PP within the range examined, yields are $\sim$ 20 times (18-24) better from extensively managed ponds than from average lake or reservoir fisheries. The conversion efficiency of

primary production to fish yields varies from 1.4% in highly productive ponds, to 1.3% in relatively unproductive ponds, which is similar to estimates for extensively managed fish ponds in Malaysia (Prowse, 1972) and India (Sreenivasan, 1972).

However, it must be borne in mind that only ponds with ΣPP over a small range (420-1640 g C m^{-2} y^{-1}) were examined. Fish yields will not continue to increase exponentially with increasing productivity, since at high productivity algae is inefficiently grazed (see Section 4.4.1 above). The turning point in the curve, where increases in ΣPP would begin to result in smaller increases in Fy probably occurs at ΣPP levels of $>$2500 g C m^{-2} y^{-1}, since Liang et al (1981) found that an expotential curve best described their data set which included ΣPP levels greater than this. The comparatively high yields at low levels of primary production in Fig. 25 are likely to be misleading, since no ponds with Σ PP 420 g C m^{-2} y^{-1} were studied. A logistic curve passing through the origin, as suggested by Liang et al (1981) is thus likely to best describe the relationship.

The yields from extensive ponds serve as a guide to the conversion efficiencies we might expect from extensively managed cages. Nevertheless, the two methods of extensive culture differ in several respects. Yields per unit primary production might be expected to be greater in cages, since predation and respiratory energy losses through foraging are likely to be higher in ponds. However, fish in deep ponds can move to cooler waters at night, thus conserving energy (Caulton, 1982). The ability of caged fish to graze algae may also be restricted, through reliance on a largely passive food supply. In view of this, and in the absence of any hard supportive data, conservative estimates of annual fish yields from extensive cage culture are probably between 1.0 and 3.5% of primary production (Table 28) which are higher than yields from managed reservoirs and lakes (Table 27). However, these values apply to ideal conditions (i.e. taking into account species and quality of fish stocked, stocking rate, mesh size, siting of cages, etc; see below) and must be used with caution.

4.4.5 Designing an extensive cage farming operation and determination of site carrying capacity

Step 1 Determine the annual gross primary production, Σ PP, of the site. Since many tropical inland water bodies exhibit seasonality in the pattern of primary production (Melack, 1979), regular measurements may have to be made.

Step 2 Convert Σ PP to potential annual fish yields, using Table 28 and Figure 25.

Step 3 The actual organisation of planned production depends on a number of variables. The number of crops per year and the size of the fish at harvest should be decided on. If, for example, tilapia are being farmed, then two crops per year of 160g fish (6 fish $kilo^{-1}$) may be desirable. However, seasonality of primary production may mean that one crop takes longer to grow. In order to reach target harvest size, the sum of primary production during the crop 1 growth period, ΣPPc1, should approximate that of crop 2, Σ PPc2, although this ignores possible change in the cropping efficiency of the fish at different algal densities, and may have to be adjusted in practice.

4.5. THE CARRYING CAPACITY OF INLAND WATERS USED FOR SEMI-INTENSIVE ENCLOSURE CULTURE

4.5.1 Introduction

Semi-intensive cage and pen culture are the most common methods of enclosure culture and also, sadly, the most difficult to evaluate and plan. The principle of semi-intensive culture is that low quality feeds are given to the fish to supplement their intake of natural food. However, as recent work carried out in the Philippines by Escover and Claveria (1984, in press) shows, at any particular site management practices vary enormously, depending on size of farm, availability of feedstuffs, and costs (Table 29).

The carrying capacity of inland waters for semi-intensive culture depends on (i) the productivity of the water body and the amount of natural food available, and (ii) the quantity and quality of supplementary food used.

4.5.2 Computation of carrying capacity

Step 1 Determine the annual primary production, ΣPP, of the site being considered, as described in Section 4.4.4 above.

Step 2 Calculate the potential annual fish yield, Fy, from the site using the information in Table 28.

Step 3 Calculate the average annual amount of the various feedstuffs being used, and the FCR, in order to determine the fish yield attributable to the supplementary food. The quantities of feedstuffs can be determined from survey work, whilst the FCR can be derived from the literature. The FCR values of some of the more common feedstuffs used in tilapia culture are given in Table 30.

Step 4 Calculate the total-P loadings associated with the use of supplementary feedstuffs, L_{fish}, and using Dillon and Rigler's (1974) model, calculate the increase in total [P] (see Step 3, Section 4.3). The increase in total [P] can be used to calculate increases in primary production, ΣPP_{fish} attributable to fish culture, although this is likely to be $< 10\%$ total fish production (see Appendix 3).

Step 5 Estimate the fish yields due to ΣPP_{fish}, using the conversion efficiencies detailed in Table 28. Calculate total fish yields from semi-intensive culture, ΣFy, as:-

$$\Sigma Fy = (a\ \Sigma PP) + (\Sigma Food \times FCR) + (b\ \Sigma PP_{fish}),$$

where a and b are expected conversion efficiencies of primary production to fish biomass (see Table 27) and $\Sigma Food$ is total amount of feedstuffs added. A worked example is shown in Appendix 3.

4.6 DISCUSSION

The models detailed above for use in estimating the environmental impact and thus the carrying capacity of inland water bodies for various

methods of cage and pen culture are at the initial stages in their development. Emphasis has been placed on cage culture, and the more commonly farmed species, such as the salmonids and tilapias.

The main problem areas associated with each model are summarised in Table 31. For intensive culture, the setting of desirable/acceptable water quality criteria is a major area of concern. Although the USEPA (1976), OECD (1982), and others have set management objectives - albeit tentative ones - these have been primarily concerned with minimising nuisance blooms in multi-use water bodies. However, a major, and as yet unresolved, area of difficulty lies in setting management objectives for water bodies where fish culture is the primary or sole activity, and where fish health is the most important consideration. As intensive fish production at a site increases, the overall water quality (turbidity, O_2, free NH_4, NO_2 levels, etc) deteriorates, and the risk of fish mortalities increases. The relationship between production and risk must be exponential, since an increasing number of mortality factors come into play with decreasing water quality, and their combined effects are synergistic rather than additive (Figure 26).

The model ignores changes in plankton species composition which can be important, since some of the blue-green algae which thrive in intensive cage culture situations can cause off-flavours (see Section 3.3.2), although farms may be willing to endure periodic problems, which they can treat (providing they have access to seawater/clean running water) in return for higher production. Similarly, some mortality due to poor water quality and disease may be acceptable from an economic standpoint. Management objectives in water bodies used solely for fish culture are thus likely to be geared towards predicting acceptable, rather than desirable, water quality standards.

The exact nature of the relationship between water quality and risk is likely to be site specific, since many local risk factors require to be considered, including species being cultured, quality of stock, timing of stocking and the prevailing water quality conditions at the site, the distance between nursery and on-growing site, management methods (e.g. frequency of grading), algal community composition, etc. All of these factors can greatly influence stock mortality, but are in practice extremely difficult to quantify. Thus the setting of acceptable water quality objectives for fish culture is still a highly contentious area. In view of this, the values in Table 20 must be used with caution to set management objectives, and these should be amended through experience and in the light of information collected from environmental monitoring.

Estimates of P-loading from intensive cage operations, L_{fish}, are likely to be revised in the near future as data on the nature of the wastes and bioavailability is published.

The model is restricted in use to P-limited water bodies, although most lakes and reservoirs fall into this category. For other types of water body, correction factors or modified P-algal biomass/primary production relationships may have been derived (e.g. Hoyer and Jones, 1983, for light limitations). The model is most applicable to small, well mixed water bodies, or to sites where the cages are widely dispersed. Cages sited near a lake or reservoir outflow may have much less impact on the water body than predicted by the model.

The overall predictive error associated with the type of model used above is large (see Reckow, 1983, for review) and seems to be principally due to the prediction of [$\overline{chl}$] and [$\overset{max}{chl}$] from [P] (OECD, 1982). According to Reckhow (1983) estimation of [P] from watershed characteristics and hydrological variables often involves errors of ± 30%, whilst the OECD (1982) data suggests the errors to be nearer ± 20%. Estimation of [$\overline{chl}$] or [$\overset{max}{chl}$] from [P] involves further errors of around ± 35% (calculated from OECD, 1982). The total error involved in predicting [$\overline{chl}$] or [$\overset{max}{chl}$] is thus around ± 55-65%. Although the magnitude of error involved seems enormous, predictions should still be good enough to act as a management guide to permissible levels of intensive fish production, which can be adjusted in the light of water quality data collected when the farm is in operation. The importance of instigating a water quality monitoring scheme cannot be stressed too highly.

The model used for extensive culture is also based on a number of untested assumptions, and therefore the conversion figures of primary production to fish biomass must be treated with care. The conclusions are based on tilapias, although data for other phytoplankton feeders, such as the silver carp, are similar (Opuzynski, 1980). Zooplankton feeders, such as bighead carp, probably convert primary production into fish biomass more inefficiently, and for this reason have been used in attempts to control eutrophication (Yang, 1982). However, further knowledge on the effects of increased predation on particular trophic levels is required, since it seems that uncontrolled zooplanktivory can lead to increases in phytoplankton biomass (Elliott et al, 1983).

Efforts to estimate optimum stocking conditions from oxygen and food supply data are woefully inadequate at present (Appendix 4), and even assuming worst possible conditions (high temperatures, low flow conditions, small fish, increased metabolic demands following meals, etc) give stocking densities which are 5-20 times greater than used in practice. In the Philippines, stocking densities in extensive cages are around 1-10 kg m^{-3}, depending on the productivity of the site. Appropriate stocking levels therefore must still be determined on a trial and error basis.

The preliminary stocking models illustrate the importance of water flow through the cages in maintaining food and oxygen supplies, and suggest that mesh sizes should be kept as large as possible, and that cages should be sited as far apart as possible in order to minimise the effects of the structures on current flow (see Fig. 27). In Selatar Reservoir, where extensive cage culture of bighead carp is carried out, cages are sited in this manner (Fig. 28).

Not surprisingly, since it is a hybrid of both the extensive and semi-intensive models, the model suggested for semi-intensive cage culture involves the errors associated with both. It is also difficult to collect information on quantities and qualities of feed being used, and in the absence of hard data, even more difficult to assess their dietary importance when being used as supplementary feeds. Nevertheless, even using the existing model, overexploitation should be reduced, and the typical pattern of lake and reservoir development (Fig. 10) changed to one which minimises financial risk to those who are most vulnerable (Fig. 29).

All the above models are concerned with cage rather than with pen culture. At present, pen culture is of much less importance and is largely restricted to a few countries in Southeast Asia (see Section 1.3). It is also only used for extensive and semi-intensive culture and may not

be suitable for all fish species. Because fish kept in pens have access to the benthos, the conversion of primary production to fish biomass is likely to be higher, although it is difficult to estimate by how much until comparative studies are carried out. Preliminary data from the Philippines suggests that production of tilapias in pens may be as high as 800 g m^{-2} $month^{-1}$ without supplementary feeding (Guerrero, 1983), which is six times greater than production of tilapias grown in cages with some supplementary feeding in the same area, during the same period (Table 32). Stocking densities were, however, different. The major drawback of this method seems to be in harvesting, and Guerrero (1983) recounts how only 15% of the fish stocked in the pens were recovered. Nevertheless, in view of these preliminary figures, a great deal more research is warranted.

Chapter 5

DISCUSSION

This report has set out to review present knowledge of the environmental impact of inland water intensive, semi-intensive and extensive methods of cage and pen culture with the aim of developing simple models which can be used to predict carrying capacity. Although a number of impact studies have been completed these have been largely concerned with the intensive culture of temperate water species, and have been focussed on qualitative rather than quantitative aspects. However, several studies are nearing completion, which should yield some of the data required to improve the models proposed above. Sadly, there are few such studies of extensive and semi-intensive enclosure culture in progress, despite rapid growth in these sectors of the industry.

Fish production from enclosures could be increased through the implementation of a number of strategies, all of which would result in a better utilisation of much pressurised resources. Wastes from intensive cage farms could be reduced by minimising P inputs to the water body and maximising P outputs. Inputs could be reduced by improving diet formulations, feed manufacturing technology, and methods of feeding fish. The P content of most commercial diets could be lowered, as P is usually present in excess of nutritional requirements, or in a form which is partially unavailable to the fish (see Section 4). The P-content of the diets is also highly variable, due to least cost formulation methods of manufacture (Tacon and De Silva, 1983). Thus, in theory the P content could be brought more into line with actual nutritional needs through improved formulations which would not only be lower in total P, but contain P in a more digestible form. Such feeds exist, but are more expensive to produce, and to date only one European manufacturer has found it profitable enough to market them. Advantages to cage fish farm operators not only include reduced risk/increased production, but also lower feed transport costs because of improved FCR (see below). However, an economic study of "low pollution" feeds and their use in cage fish farming is required in order to fully evaluate profitability.

Both extruded and expanded steam conditioned pellets have lower dust levels (Hilton *et al*, 1981), and the extruded type also float and have greater stability in water (Stickney, 1979), thus reducing the proportion of uneaten feeds. The FCR of extruded, steam-conditioned floating pellets seems to be better (Suwanasart, 1972; Hilton *et al*, 1981), although the carbohydrate fraction in the diet is increased to such an extent through the manufacturing process, that in rainbow trout at least, liver function could be impaired (Hilton *et al*, 1981). However, several novel feed manufacturing processes, which seem to improve pellet durability and which would thus reduce waste levels, are currently being evaluated (ADCP, 1983).

Little research has been carried out on feed presentation, and it is therefore difficult to conclude which method - manual/mechanical, automatic/demand - is best. Feed consumption pattern varies with species, size and temperature, but in the absence of hard data hand feeding is usually recommended for artisanal farming, whereas automatic feeders are recommended for more intensive operations. According to Goddard and Scott (1980), fish in cages should be fed over longer periods of time (i.e. the ration should be delivered to the cage at a slower rate), due to the relatively small surface area to volume ratio, compared with ponds.

However, the designs of present-day mechanical feeders used in cages are generally the same as those used in ponds and raceways, and should be examined more closely with the aim of reducing feed losses.

The net P loading to the environment could be reduced by application of a number of conventional lake and reservoir restoration techniques. Point-source control, or diversion of wastes from the water body, is a common method of reducing loadings (Welch, 1980), and has been demonstrated as technically feasible at enclosure fish farm sites by Tucholski et al (1980, 1980), who trapped the particulate waste fraction from cages and pumped them ashore. Sediment removal has also been used in restoration programmes (Jørgensen, 1980), but has not yet been attempted at inland water cage or pen sites. Submersible mixers, consisting of a large, electrically-driven propellor, have been used to disperse sedimented wastes from under marine cages, but would probably cause more problems than they would solve if used in inland sites. Here, the resuspension of sediments might halt localised H_2S production, but would also be likely to stimulate algal production through increasing dissolved nutrient levels and destroying the thermocline. The actual removal of sediment from under cages is necessary, and this is prohibitively expensive (Welch, 1980). Tucholski et al's method of waste diversion would also be expensive, and impractical in commercial-sized operations.

Other, more practical methods of reducing impact from intensive farms include removal of mortalities and increased fisheries pressure. Penczak et al demonstrated that removal of dead rainbow trout from cages reduced the annual total-P loading to the lake by 10%. The capture and removal of escaped fish, through netting or angling can also help. In one cage rainbow trout farming operation in Scotland, for example, which produces in excess of 200 tonnes per annum, 10 tonnes were harvested through netting of escaped fish, whilst a further 2.5 tonnes were removed by anglers (A. Stewart, pers. comm.). This not only generated additional income to the farm, but also reduced the annual total-P loading to the lake by up to 1.3% (assuming 1.5:1 FCR, P content of feed = 1.5%, and P content of fish carcasses = 0.48% wet weight. See Section 4.4. Estimated reductions in waste outputs from intensive cage operations, based on methods suggested above, are summarised in Table 33.

Another, and as yet unresearched method of reducing the environmental impact of intensive cage fish farming, whilst improving the utilisation of water bodies for fish production would be to combine extensive with semi-intensive or extensive operations. In this way, expensive-to-culture fishes, such as gourami, which require high protein diets, could be reared alongside inexpensive species such as the tilapias or carps, the sale of which would help offset the costs of feed. The potential for such a scheme is considerable, and may make intensive enclosure culture, currently regarded as being marginally feasible in some tropical developing countries, a more realistic proposition. Such a scheme may also have potential in temperate countries, providing species suitable for extensive culture, from both technical and economic viewpoints, could be found. Greatest potential here probably lies in the use of carps, whitefish, and the planktivorous stages of carnivores, such as pike.

Despite careful planning, and minimising of any adverse impacts, it is highly probable that some types of inland water body will prove unsuitable for cage or pen culture. For example, in fast-flowing reaches of rivers and streams, high feed losses will affect the viability of intensive and semi-intensive operations (see Section 2.2). If extensive culture is practiced in such systems, then care must be taken to ensure

that there is adequate natural food available for the particular species being farmed (see Othman et al, 1983). In some lentic systems there may also be insufficient food to support extensive culture. If, for example, primary production in a typically unproductive lake is around 50 g C m^{-2} y^{-1}, then fish production of 50 kg ha^{-1} y^{-1}, assuming a food conversion efficiency of 1%, might be expected. Thus a single cage measuring 5 x 5 x 5 m, and stocked with 5 fish m^{-3} would require all the algae produced in a 1 km^{-2} (10 ha) area, in order for the fish to reach a market size of 150 g. However it is uncertain (but doubtful) whether a single cage of fish would have access to all the algal production from such a large area, and at this level of primary production, the feasibility of extensive culture looks unpromising.

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Table 1 Commercially important species in inland water cage and pen farming

Species		Countries	Climate	Type of feeding	Lotic/Lentic	Cage/Pen
Salmonids	Rainbow trout	Europe, North America, Japan, high altitude tropics (eg Colombia, Bolivia, Papua New Guinea)	Temperate	Intensive. High protein (40%)	Lentic	Floating cage
	Salmon (various species) smolts	Europe, North America, South America, Japan	Temperate	Intensive. High protein (45%)	Lentic	Floating cage
Carps	Chinese carps (Silver carp, grass carp, bighead carp)	Asia, Europe, North America	Temperate - tropical	Mainly semi-intensive, although also extensive (Asia) and intensive (Europe, North America)	Lotic and lentic	Cages and pens
	Indian major carps (*Labeo rohita*)	Asia	Sub-tropical - tropical	Semi-intensive	Mainly lentic	Mainly cages
	Common Carp	Asia, Europe, North America, South America	Temperate - tropical	Mainly semi-intensive, although also intensive	Mainly lentic	Mainly cages
Tilapias (*O. mossambicus*, *O. niloticus* etc)		Asia, Africa, North America, South America	Sub-tropical - tropical	Mainly semi-intensive, although also intensive	Mainly lentic	Mainly cages
Catfishes	Channel catfish	North America	Temperate - sub-tropical	Intensive	Lentic	Floating cages
	Clarias spp.	Southeast Asia, Africa	Tropical	Semi-intensive	Lotic and lentic	Floating cages
Snakeheads	*Channa* spp. *Ophicephalus* spp.	Southeast Asia	Tropical	Semi-intensive/ intensive	Lotic and lentic	Floating cages
Pangasius spp.		Southeast Asia	Tropical	Semi-intensive	Lentic	Floating cages
Milkfish		Southeast Asia	Tropical	Semi-intensive	Lentic	Pens

Table 2: Advantages and limitations of cage fish culture technique (from Balarin and Haller, 1982)

Advantages	Limitations
Possibility of making maximum use with the greatest economy of all the available water resources	Difficult to apply when the water surface is very rough therefore location restricted to sheltered areas
Helps reduce the pressures on land resources	Back up food store hatchery and processing units necessary therefore requires strategic location
Possibilities of combining several types of culture within one water body, the treatments and harvests remaining independent	
Ease of movement and relocation	
Intensification of fish production (i.e. high densities, optimum feeding results in improved growth rates and reduces length of rearing period)	Need an adequate water exchange through the cages to remove metabolites and maintain high dissolved oxygen levels. Rapid fouling of cage walls requires frequent cleaning
Optimum utilisation of artificial food for growth, improves food conversion efficiencies	Absolute dependence on artificial feeding unless utilised in sewage ponds. High quality balanced rations essential. Feed losses possible through cage walls
Easy control of competitors and predators	Sometimes important interference from the natural fish population, i.e. small fish enter cages and compete for food
Ease of daily observation of stocks allows for better management and early detection of disease. Also economical treatment of parasites and diseases	Natural fish populations act as a potential reservoir of disease or parasites and the likelihood of spreading disease by introducing new cultured stocks is increased
Easy control of tilapia reproduction	
Reduces fish handling and mortalities	Increased difficulties of disease and parasite treatment
Fish harvest is easy and flexible, and can be complete and of a uniform product	Risks of theft are increased
Storage and transport of live fish is greatly facilitated	Amortisation of capital investment may be short
Initial investment is relatively small	Increased labour costs for handling, stocking, feeding and maintenance

Table 3: Theories proposed to explain floating and stationary Fish Attraction Devices (FAD's), and their applicability to inland water cage and pen structures.

		Applicability
1.	Use as cleaning stations where external parasites of pelagic fishes can be removed by other fishes	-
2.	Shade	*
3.	Creates shadow areas in which zooplankton become more visible	*
4.	Provides substrate for egg laying	-
5.	Drifting object serves as schooling companion	-
6.	Provides spatial reference around which fishes could orient in an otherwise unstructured environment	*
7.	Provides shelter from predators for small fishes	**
8.	Attracts larger fishes because of presence of smaller fishes	**
9.	Acts as substrate for plant and animal growth, thus attracting grazing fishes	**

from M. Seki, 1983. Summary of pertinent information on the attractive effects of artificial structures in tropical and subtropical waters. Unpublished administrative report of the Southwest Fisheries Center, Honolulu. 49 p.

Table 4: Predators reported from cage and pen fish farms. Data taken from Salmon and Conte (1982), Martin (1982) and Ranson and Beveridge (1983)

Predator		Country
Snakes	(*Natrix* sp)	USA
Birds	Grebes	USA
	Herons	USA, Europe
	Egrets	USA
	Cormorants	USA, Europe
	Ducks	USA, Europe
	Gulls	USA, Europe
	Kites	SE Asia[1]
	Ospreys	USA, Europe
Rodents	Muskrats	USA
	Rats	SE Asia[1]
Mustelids	Otters	USA, Europe, SE Asia[1]
	Mink	USA, Europe

[1] From personal observation

Table 5: Summary of the results from studies of the environmental impacts of intensive cage fish culture in various countries

WATER BODY	SIZE	CULTURED SPECIES	PRODUCTION (T annum^{-1})	DURATION OF CULTURE	IMPACT	NO DETECTABLE IMPACT	COMMENTS	REFERENCE
Bull Shoals Reservoir, Arkansas, USA Built 1961	-	rainbow trout channel catfish blue catfish	~205	5 years	increase: NH_4, total-P, green algae, diatoms, protozoa, game & coarse fish decrease: secchi disc build up: faecal material under cages	O_2, temp, NO_3, NO_2, turbidity, CO_2, pH, alkalinity, conductivity, blue-green algae, rotifers, desmids.	Changes localised in bay where cages sited	Hays, 1982
White Oak Lake, Arkansas, USA Reservoir, built 1960	1083 ha	channel catfish	~150	2 years	increase: turbidity, alkalinity, total-P, PO_4-P, organic N, BOD, bacteria, zooplankton, benthic invertebrates, primary production. decrease: dissolved O_2, NO_3, chlorophyll a	temp, COD	Cages localised near outflow	Eley et al, 1972
Crystal Lake, Arkansas, USA	24 ha	channel catfish rainbow trout	~9	1 year	increase: turbidity, PO_4-P, NO_3, NO_2, phytoplankton, zooplankton, oligochaetes, fish populations decrease: culicids	temp, O_2, pH, NH_4	3 sampling sites chosen	Kilambi et al, 1976

Table 5 (contd.)

WATER BODY	SIZE	CULTURED SPECIES	PRODUCTION (T annum^{-1})	DURATION OF CULTURE	IMPACT	NO DETECTABLE IMPACT	COMMENTS	REFERENCE
Lake Hartwell, South Carolina, USA	24,300	channel catfish	0.15	5 months	increase: local fish populations	-	Small, experimental cages. Only effects on fish community studied	Loyacano and Smith, 1976
Lake Keowee, South Carolina, USA	7,300	channel catfish	0.43	12 months	increase: local fish populations	-	Small, experimental cages. Only effects on fish community studied	Loyacano and Smith, 1976
Lake Glebokie, Poland	47.3 ha	rainbow trout	$\sim$18	5 years	increase: C, total-P, total N	-	Only C, P, and N budgets examined	Penczak et al, 1982
Dgal Wielki, Poland	93.9	carp and tench	-	4 years	increase: BOD, suspended solids, P content of seston decrease: O_2	PO_4, NH_4, NO_3	-	Korycka and Zdanowski, 1980
Lake Skarsjon, Norway	310 ha	rainbow trout	20	3 years	increase: total-P, and in sediments total-P, total-N, O_2 consumption decrease: redox potential in sediments	total-P, NH_4, NO_3 & NO_2, Kjeldahl-N in water	Work concentrated on sediments	Enell, 1982
Lake Byajon, Norway	140 ha	rainbow trout	15	3 years	increase: total-P, and in sediments total-P, total-N, O_2 consumption decrease: redox potential in sediments	total-P, NH_4, NO_3 & NO_2, Kjeldahl-N in water	Work concentrated on sediments	Enell, 1982

Table 6: Extensive cage tilapia production figures from the Philippines

Lake	Date	Cage size (m)	Stocking Density (m^{-3})	Size at stocking (g)	Culture Period (months)	Size at Harvest (g)	Production ($kg\ m^{-3}\ month^{-1}$)	Reference
Bunot	1980	20 x 25 x 5	4	-	4	250	0.24	Alvarez, 1981
Laguna de Bay	1978	5 x 10 x 3 - 10 x 20 x 5	4-8	~1	4-5	100	0.07-0.18	Mane, 1979
Sampaloc	1983	10 x 10 x 9 - 25 x 20 x 9	1.6-2.0	12.5-16.0	6-9	225-300	0.05-0.08	Guerrero, 1983
Taal	1983	10 x 5 x 3	50	-	4	100	1.25	Guerrero, 1983
Bato	1983	-	50	-	4	160	1.90	Job Bisuña, pers. com.
Buluan	1982-3	5 x 10 x 5	10	~1	5	200	0.40	Oliva, 1983

Table 7: Life span of various materials used in temperate and tropical cage and pen construction (modified from IDRC/ SEAFDEC, 1979)

Materials	Life expectancy in fresh waters
Bamboo and logs	1-2 years
Metal drums	0.5-3 years
Rubber tyres*	5+ years
Used plastic drums	1.2+ years
Styrofoam - covered	5+ years
- not covered	2+ years
Ferrocement	10+ years
PVC Pipes	5+ years
Spherical buoys - aluminium	10+ years
- plastic	5 years
Aluminium cylinders	10+ years

* Polystyrene filled

Table 8: The relative supply and demand of elements required by plants and algae and derived from soils and rocks (lithosphere) of the catchment area (from Moss, 1980)

Element	(1) Ratio of amount of element to that of phosphorus in the lithosphere	(2) Ratio of amount required of element to amount required of phosphorus in plants and algae	Ratio of (1) to (2)
Na	32.5	0.52	43
Mg	22.2	1.39	16
Si	268.1	0.65	410
P	1.0	1.0	1.0
K	19.9	6.1	3.3
Ca	39.5	7.8	5.1
Mn	0.90	0.27	3.3
Fe	53.6	0.06	880
Co	0.02	0.0002	110
Cu	0.05	0.006	8.5
Zn	0.07	0.04	1.5
Mo	0.0014	0.0004	3.6

Table 9: N:P ratios (by weight) in a range of freshwater bodies

Data base	No.	Ratio	% above ratio	Reference
Lakes and reservoirs from all over the world	54	>5:1 total-N:total P	85	Schindler, 1978
European and North American lakes and reservoirs	89	>7:1 inorganic N:PO_4-P	85	OECD, 1982
Shallow water bodies in Europe and North America	70	>7:1 inorganic N:PO_4-P	95	Clasen, 1981
Reservoirs in Missouri and Iowa, USA	6	>7:1 total-N:total-P	99	Hoyer and Jones 1983
Lakes off the Pre-Cambrian Shield, Canada	22	>12:1 total-N:total-P	95	Prepas and Trew, 1983
Kenyan lakes	8	>9:1 total N:total-P	100	Kalff, 1983
Southern African man-made lakes	25	>7:1 variable	68	Walmsley and Thornton, 1984 (in press)

Table 10: Dietary phosphorus requirements of fish, expressed as percentage weight of diet (after Beveridge et al, 1982).

Species	Requirement	Source
Anguilla japonica	0.29%	Arai et al, 1975
Salmo trutta	0.71%	McCartney, 1969
Salmo salar	0.30%	Ketola, 1975
Salmo gairdneri	0.70-0.80%	Ogino and Takeda, 1978
Oncorhynchus keta	0.50-0.60%	Watanabe et al, 1980a
Cyprinus carpio	0.60-0.80%	Ogino and Takeda, 1976
Ictalurus punctatus	0.45-0.80%	Andrews et al, 1973; Lovell, 1978
Chrysophrys major	0.68%	Sakomoto and Yone, 1980
Oreochromis niloticus	0.90%	Watanabe et al, 1980b

Table 11: Ranges and mean values (%) of total-P content of commercially available salmonid diets in the U.K. Data based on the analysis of feeds produced by six manufacturers.

	Starter	Fingerling	Grower	Broodstock
Trout (mean)	1.48	1.49	1.50	1.45
(range)	0.95-2.82	1.09-2.16	1.08-2.18	0.96-1.62
Salmon (mean)	1.46	1.55	1.19	
(range)	1.15-2.05	1.15-2.05	0.94-1.71	

Data from Tacon and De Silva (1983).

Table 12: Total-P content (% wt.) of carp and tilapia diets used in intensive culture in various parts of the tropics

(a) Tilapias

Country	Diet	P content of ingredients (%)	P in diet (%)	
Philippines	DIET 1			
	75% rice bran ('cono')	0.41	0.31	
	25% fish meal	3.97	0.99	1.30
	DIET 2			
	65% rice bran ('cono')	0.41	0.27	
	10% copra meal	0.60	0.06	1.32
	25% fish meal	3.97	0.99	
Central African Republic	82% Cottonseed oilcake	1.05	0.86	
	8% Wheatflour	0.11	0.01	
	8% Cattle blood meal	0.29	0.02	1.29
	2% Bicalcium phosphate	20.00	0.40	
Ivory Coast	DIET B1			
	65% Rice polishings	1.32	0.86	
	12% Wheat middlings	0.83	0.10	
	18% Peanut oilcake	0.50	0.09	1.19
	4% Fishmeal	3.58	0.14	
	1% Oyster shell	0.07	-	
	DIET B2			
	61% Rice polishings	1.32	0.81	
	12% Wheat middlings	0.83	0.10	
	18% Peanut oilcake	0.50	0.09	1.29
	8% Fishmeal	3.58	0.29	
	1% Oyster shell	0.07	-	
	DIET B3			
	65% Rice polishings	1.32	0.86	
	12% Wheat middlings	0.83	0.10	
	18% Cottonseed oilcake	1.10	0.20	1.30
	4% Fishmeal	3.58	0.14	
	1% Oystershell	-	-	
	DIET B4			
	15% Brewery waste	0.53	0.08	
	15% Maize bran	0.80	0.12	
	15% Rice bran	0.43	0.65	
	12% Wheat middlings	0.83	0.10	1.51
	38% Cottonseed oilcake	1.10	0.42	
	4% Fishmeal	3.58	0.14	
	1% Oyster shell	-	-	
UK(35g fish)	5% Brown fishmeal	3.97	0.20	
	3% Hydrolysed feathermeal	0.70	0.02	
	5% Meatmeal	1.40	0.07	
	4% Soybean meal	0.67	0.03	
	10% Groundnut meal	0.50	0.05	
	20% Cottonseed meal	1.05	0.21	1.25
	37% Rice bran	0.41	0.15	
	10% Dried distillers sol.	-	-	
	2% Vitamin premix	-	-	
	4% Mineral premix	13.10	0.52	

(b) Carps

Country	Diet	P content of ingredients (%)	P in diet (%)	
Europe	DIET 1			
	25% Soybean meal	0.63	0.16	
	10% Fishmeal	3.58	0.36	
	10% Meatmeal	1.40	0.14	
	5% Lucerne meal	-	-	1.03
	25% Rice bran	0.43	0.11	
	20% Rice polish	1.32	0.26	
	5% Distillers solubles	-	-	
	DIET 2			
	25% Soybean meal	0.63	0.16	
	10% Fishmeal	3.58	0.36	
	10% Meatmeal	1.40	0.14	
	20% Wheat middlings	0.83	0.17	0.94
	5% Lucerne meal	-	-	
	25% Rice bran	0.43	0.11	
	5% Distillers solubles	-	-	
USA	46% Fishmeal	3.58	1.65	
	28% Wheat middlings	0.83	0.23	
	7% Rice bran	0.43	0.03	
	5% Wheat bran	1.27	0.06	
	5% Soybean seeds	0.63	0.03	
	4% Yeast	1.67	0.07	3.09
	1.5% Corn gluten	0.47	0.01	
	0.5% Vitamin premix	0	0	
	0.5% Mineral premix	13.10	0.66	
	0.5% Sodium chloride	0	0	
	2% Potassium phosphate	17.64	0.35	

Tilapia diet formulations from Coche (1982), Jauncey and Ross (1982). Carp diet formulations from Pearson (1967) and NRC (1977). P content of feedstuffs from NRC (1977) and Santiago (1983).

Table 13: Recommended food particle sizes for salmonids and tilapias. The term 'crumb' refers to round particles, whereas 'pellet' refers to cylindrical ($l \leq 3d$) particles. Sizes refer to particle diameter (d).

(a) Trout

Fish size (g)	Pellet size (mm)	
0.4	0.3-0.6	crumb
0.4-1	0.4-1.0	crumb
1-3	1.1-1.5	crumb
3-9	1.5-2.0	crumb
9-20	2.0-3.0	crumb
9-20	1.5	pellet
20-40	2.0	pellet
35-110	3.0	pellet
90-300	5.0	pellet
200-800	6.5	pellet
750+	8.0	pellet

(b) Tilapias

Fish size (g)	Pellet size (mm)	
Fry first 24 hrs	liquifry*	
0.015	0.5	crumb
0.015-0.15	0.5-1.0	crumb
0.5-1.0	0.5-1.5	crumb
1-30	1.0-2.0	crumb
20-120	2.0	pellet
100-250	3.0	pellet
250+	4.0	pellet

* Tilapia data from Macintosh (1984), Macintosh and De Silva (1984), Jauncey and Ross (1982). Trout data from Ewos-Baker.

Table 14: Summary of data from Glebokie Lake, Poland (Penczak et al, 1982). Units in kg, and total losses (F + C + U; see p. 41 for terminology) calculated assuming mortalities were not removed from the lake.

	Generation 2 (June 1976-Dec. 1977)	Generation 3 (Jan. 1978-Dec. 1978)
Fish Production	27,534	11,000
total-C losses	16,708	9,701
total-P losses	507	291
total-N losses	2,094	1,296
C losses per kg trout production	0.607	0.890
P losses per kg trout production	0.019	0.026
N losses per kg trout production	0.076	0.118

Average (Gen. 2 and Gen 3) C losses per kg trout production = 0.748
P losses per kg trout production = 0.023
N losses per kg trout production = 0.097

Table 15: Feed Conversion Ratios (FCR's) for various intensive trout and tilapia diets. The composition of tilapia diets are detailed in Table 12

(a) Trout

Feed Brand/ Type	Feed Form	Crude Protein Level (%)	Culture System	FCR	Reference
Commercial, various	Pellets, dry, sinking	40-41	Ponds Ponds	1-3:1 1-28:1	Edwards, 1978 Templeton & Jarrams, 1980
EWOS, T-4D	Pellets, dry, floating	47%*	Tanks	0.94:1	Ketola, 1982
Abernathy	Pellets, dry, sinking	-	Tanks	1.19:1	Ketola, 1982
Purina Trout Chow	Pellets, dry, floating	40	Cages	2.09-3.26:1	Kilambi et al, 1976
	Pellets, dry, sinking	40*	Cages	1.59-2.73:1	Templeton & Jarrams, 1980

(b) Tilapia

Feed Brand/ Type	Feed Form	Crude Protein Level (%)	Culture System	FCR	Reference
Philippines, Diet 1	Mash, moist, sinking	24.2	Cage	2.57:1	Guerrero, 1980
Philippines, Diet 2	Mash, moist, sinking	24.3	Cage	2.58:1	Guerrero, 1980
Central African Republic Diet	Pellets, sinking	-	Cage	3.20:1	Coche, 1982
Ivory Coast Diets B_1 + B_4	Pellets, dry, sinking	20-25	Cage	2.0-2.40:1	Coche, 1982

* Estimated

Table 16: Theoretical calculations of total-P released into the environment during intensive cage culture of trout and tilapia.

(a) Rainbow trout

Phosphorus content of commercial trout pellets 1.50%[a]
∴ 1 tonne feed contains 15.0 kg

Food Conversion Ratio (FCR) = 1.0:1, P_{food} = 15.0 kg
FCR = 1.5:1, P_{food} = 22.5 kg
FCR = 2.0:1, P_{food} = 30.0 kg
FCR = 2.5:1, P_{food} = 37.5 kg

Phosphorus content of trout = 0.48% wet weight of fish[b] = 4.8 kg tonne $fish^{-1}$

∴ Phosphorus release to environment (P_{env}):-

1.0:1 FCR = 15-4.8 = 10.2 kg tonne fish $prod^{-1}$
1.5:1 FCR = 22.5-4.8 = 17.7 kg " " "
2.0:1 FCR = 30.0-4.8 = 25.2 kg " " "
2.5:1 FCR = 37.5-4.8 = 32.7 kg " " "

(b) Tilapia

Phosphorus content of compounded feeds (see Table 12) 1.30%
∴ 1 tonne feed contains 13.0 kg

Food Conversion Ratio (FCR) = 2.0:1 P_{food} = 26.0 kg
2.5:1 P_{food} = 32.5 kg
3.0:1 P_{food} = 39.0 kg
3.5:1 P_{food} = 45.5 kg
4.0:1 P_{food} = 52.0 kg

Phosphorus content of tilapia = 0.34% wet weight of fish[c] = 3.4 kg tonne $fish^{-1}$

∴ Phosphorus release to environment (P_{env}):-

2.0:1 FCR = 26.0-3.4 = 22.6 kg tonne fish $produced^{-1}$
2.5:1 FCR = 32.5-3.4 = 29.1 kg " " "
3.0:1 FCR = 39.0-3.4 = 35.6 kg " " "

a = Average P content of commercial grower feeds used in Europe. Data from Tacon and De Silva (1983).

b = data from Penczak et al (1982)

c = P content of tilapia, estimated from Meske and Manthey (1983), assuming dry weight = 25% wet carcasse weight

Table 17: Total-P loadings associated with intensive land-based salmonid culture (modified from Beveridge et al, 1982)

$\frac{P}{fish}$ (kg tonne production^{-1})	Source
40.15 P	Liao and Mayo, 1972
15.70 P	Solbe, 1982
36.50 total-P 18.25 PO_4-P	Warrer-Hansen, 1982
10.95-113.15 total-P	Alabaster, 1982
18.32 total-P	Sumari, 1982
9.10-22.77 total-P	Ketola, 1982

Table 18: Food Conversion Ratios (FCR) of rainbow trout grown in cages and in ponds, using commercial dry pellets as food source

	FCR	Reference
Ponds	1.00-3.00:1	Edwards, 1978
	1.28:1	Templeton and Jarrams, 1980
	1.20-1.40:1	Stevenson, 1980
	1.50:1	Bardach et al, 1973
Cages	2.09-3.26:1	Kilambi et al, 1976
	1.50-1.80:1	Landless, 1980
	1.59-2.73:1	Templeton and Jarrams, 1980
	1.50:1	Enell, 1982
	1.60-2.00:1	Coche, 1978a
	3.40-3.70:1	Korycka and Zdanowski, 1980

Table 19: Summary of [P] predictive models (r = correlation coefficient; S.E. = standard error)

Model type	Model	Data Base	Performance	Reference
Vollenweider, 1976	$\overline{[P]} = \frac{L}{q_s(1 + T_w^{\frac{1}{2}})}$	68 mid-western reservoirs, USA	r = 0.64; S.E. = 0.39	Mueller, 1982
		32 Southern African reservoirs (42 observations)	difference between predicted and observed: n = 42; x^2 = 4.90; P 0.01	Thornton and Walmsley, 1982
Jones-Bachmann, 1976	$\overline{[P]} = \frac{0.84L}{\bar{z}(0.65 + \rho)}$	75 North American lakes		Jones and Bachmann, 1976
		68 mid-western reservoirs, USA	r = 0.65; S.E. = 0.37	Mueller, 1982
	$\overline{[P]} = \frac{0.49L}{\bar{z}(0.0926(L/Z)^{0.510} + \rho)}$	704 natural and artificial lakes in Europe and North America	r = 0.81	Canfield and Bachmann, 1981
	$\overline{[P]} = \frac{0.8L}{\bar{z}(0.0942(L/Z)^{0.422} + \rho)}$	271 natural lakes in Europe and North America	r = 0.82	Canfield and Bachmann, 1981
	$\overline{[P]} = \frac{0.8L}{\bar{z}(0.0569(L/Z)^{0.639} + \rho)}$	433 artificial lakes in Europe and North America	r = 0.82	Canfield and Bachmann, 1981
	$\overline{[P]} = \frac{0.603L}{\bar{z}(0.257 + \rho)}$	704 natural and artificial lakes in Europe and North America	r = 0.77	Canfield and Bachmann, 1981

Table 19 (contd.)

Model type	Model	Data Base	Performance	Reference
Dillon-Rigler, 1974	$[\bar{P}] = \frac{L(1-R)}{\bar{z}\rho}$	18 Canadian lakes	-	Dillon and Rigler, 1974
		68 mid-western reservoirs, USA	r = 0.86; S.E. 0.20	Mueller, 1982
		32 Southern African reservoirs (37 observations)	difference between predicted and observed n = 37; x^2 = 1.83; p < 0.001	Thornton and Walmsley, 1982
OECD - 1982	$[\bar{P}] = \frac{L}{1+\sqrt{T_W}}$	87 lakes in Europe and North America	r = 0.93	OECD, 1982
		14 Nordic lakes	r = 0.86	OECD, 1982
		18 Alpine lakes	r = 0.93	OECD, 1982
		31 North American lakes	r = 0.95	OECD, 1982
		24 shallow lakes and reservoirs in North America and Europe	r = 0.95	OECD, 1982

Table 20: Tentative[1] values for maximum acceptable $[\overline{P}]$ in lentic inland water bodies used for enclosure culture of fish

Water Body Category	Species Cultured	Tentative maximum acceptable [P]
Temperate	Salmonid	60
	Carp	150
Tropical	Carp & tilapia	250

[1] see text (4.3.3.2 and 4.6)

Table 21: Regression equations relating annual mean chlorophyll levels $[\overline{chl}]$ and peak chlorophyll levels $[\overset{max}{chl}]$ to each other, and to mean in-lake total phosphorus concentrations $[\overline{P}]$. N.B. Three equations are given for each relationship except the last (see text). Units = mgm^{-3}.

(a) Relationships between $[\overline{chl}]$ and $[\overline{P}]$

(i)	$[\overline{chl}] = 0.61\ [\overline{P}]^{.69}$	n = 99;	r = 0.75;	S.E. = 0.335
(ii)	$[\overline{chl}] = 0.38\ [\overline{P}]^{.86}$	n = 88;	r = 0.86;	S.E. = 0.272
(iii)	$[\overline{chl}] = 0.28\ [\overline{P}]^{.96}$	n = 77;	r = 0.88;	S.E. = 0.251

(b) Relationships between $[\overset{max}{chl}]$ and $[\overline{P}]$

(i)	$[\overset{max}{chl}] = 1.77\ [\overline{P}]^{.67}$	n = 65;	r = 0.70;	S.E. = 0.375
(ii)	$[\overset{max}{chl}] = 0.90\ [\overline{P}]^{.92}$	n = 54;	r = 0.86;	S.E. = 0.296
(iii)	$[\overset{max}{chl}] = 0.64\ [\overline{P}]^{1.05}$	n = 50;	r = 0.90;	S.E. = 0.257

(c) Relationships between $[\overset{max}{chl}]$ and $[\overline{chl}]$

(i)	$[\overset{max}{chl}] = 2.86\ [\overline{chl}]^{1.03}$	n = 73;	r = 0.93;	S.E. = 0.199
(ii)	$[\overset{max}{chl}] = 2.60\ [\overline{chl}]^{1.06}$	n = 72;	r = 0.95;	S.E. = 0.167

data derived from OECD (1982)

Table 22: Relationship between $[\overline{chl}]$ and ΣPP in some tropical lakes

Lake	$[\overline{chl}]$	ΣPP	Reference
Madden	6 mg m^{-3}	600 mg O_2 $m^{-2}h^{-1}$	Gliwicz, 1976
Chad	18 mg m^{-3}	45 g O_2 $m^{-2}d^{-1}$	Lemoalle, 1975
Victoria	44 mg m^{-3}	7.4 g O_2 $m^{-2}d^{-1}$	Talling, 1965
Naivasta Crater	45 mg m^{-3}	4.9 g O_2 $m^{-2}d^{-1}$	Melack, 1979
McIlwaine	93 mg m^{-3}	3.9 g O_2 $m^{-2}d^{-1}$	Robarts, 1978
Elementia	97 mg m^{-3}	570 mg O_2 $m^{-2}h^{-1}$	Melack, 1979
Castanho	127 mg m^{-2}	2.8 g O_2 $m^{-2}d^{-1}$	Schmidt, 1973
George	400 mg m^{-2}	7.4 g O_2 $m^{-2}d^{-1}$	Ganf, 1974, 1975

Table 23: Empirical models for calculating the sedimentation rate, σ, retention coefficient, R ($^1/_\rho$), and the sedimentation coefficient, V, of phosphorus, for both general and specific categories of temperate water bodies

Model type	Size of data base	Model		Correlation coefficient	Source
(a) General. U.S. EPA data base & several European lakes and reservoirs	704	$\sigma = 0.129\ (L/\bar{z})^{0.549}$		0.81	Canfield and Bachmann, 1981
		$R = \frac{1}{(1 + 0.614\rho^{0.491})}$	*	0.79	Larsen and Mercier, 1976
		$\sigma = 0.94$	*	0.79	Jones and Bachmann, 1976
		$V = 2.99 + 1.7q_s$	*	0.73	Reckhow, 1979
		$V = 5.3$	*	0.71	Chapra, 1975
	73	$R = \frac{1}{1 + \rho^{0.5}}$		0.79	Larsen and Mercier, 1975
		$\sigma = 0.65$		0.79	Jones and Bachmann, 1976
		$R = 0.426\ \exp(-0.271q_s) + 0.574\exp(-0.00949q_s)$		0.71	Kirchner and Dillon, 1975
		$V = 11.6 + 1.2q_s$		0.68	Reckhow, 1979
		$\sigma = 10/\bar{z}$		0.68	Vollenweider, 1975
		$V = 12.4$		0.66	Chapra, 1975
(b) Reservoirs. North American	210	$\sigma = 0.114\ (L/\bar{z})^{0.589}$		0.83	Canfield and Bachman, 1981
		$R = \frac{1}{(1 + 0.515\rho^{0.551})}$	*	0.80	Larsen and Mercier, 1976
(c) Natural lakes	151	$\sigma = 0.162\ (L/\bar{z})^{0.458}$		0.83	Canfield and Bachmann, 1981
		$R = \frac{1}{(1 + 0.747\rho^{0.507})}$	*	0.80	Larsen and Mercier, 1976
(d) Lakes with low flushing rates (q_s < 10m)	53	$R = 0.201\ \exp(-0.0425q_s) + 0.574\exp(-0.00949q_s)$		-	Ostrofsky, 1978

q_s = areal water loading (mg^{-1})
ρ = flushing rate (volumes per year)
* = coefficients recalculated by Canfield and Bachmann (1981) using their data base

Table 24: Diet of tilapias and carps commonly used in aquaculture (tilapia data modified from Jauncey and Ross, 1982)

Species	Diet
O. mossambicus	Adults omnivorous, but feed mainly on plankton, vegetation and benthic algae. Juveniles feed initially entirely on zooplankton.
O. niloticus	Adults omnivorous, but feed predominantly on phytoplankton, and can utilise blue-green algae. Juveniles consume wider range of food items.
H. molitrix	Adults and juveniles feed largely on phytoplankton, although they will ingest detritus and zooplankton, providing the particle size is within the range 8-100 μm.
A. nobilis	Adults feed on larger phytoplankton, zooplankton and detritus particles within the size range 17-3000 μm.

Table 25: Assimilation efficiencies (Aε) of tilapias feeding on various diets (modified from Bowen, 1982)

Species	Diet	Component	A
O. niloticus	Microcystis sp.	^{14}C	70
	Anabaena sp.	^{14}C	75
	Nitzschia sp.	^{14}C	79
	Chlorella sp.	^{14}C	49
	Lake George suspended matter	total C	43
O. mossambicus	Najas guadalupensis	dry wt.	29
		protein	75
		energy	45
T. rendalli	Ceratophyllum demersum	dry wt.	53-60
		protein	80
		energy	48-58

Table 26: Increases in yields from lake fisheries in China, following the implementation of stocking and other management policies. Data from FAO (1983).

Lake	Size (ha)	Yield prior to stocking, etc.	Yield subsequent to stocking, etc.	% increase in yield
Baitan Hu, Hubei	400	450 kg ha	750 kg ha	67
Xi Hu, Zhejiang	559	35 kg ha	536 kg ha	1431
Dianshan Hu, Shanghai	6,670	48 kg ha	75 kg ha	56
Tai Hu, Jiangsu	226,700	24 kg ha	56 kg ha	133

Table 27: The relationship between gross areal photosynthetic rates and fish yields from seven suburban lakes near Wuhan, China (data from Liang et al, 1979). Efficiencies of energy transfer (fish yield/primary production) are based on a conversion factor of 0.375 for photosynthetic O_2 production → photosynthetic C production (APHA, 1980), and a fresh fish C content of 10% (Gulland, 1970).

Lake	Gross photosynthetic rate (g C $m^{-2}y^{-1}$)	Gross fish yield (g $m^{-2}y^{-1}$)	Net fish yield (g $m^{-2}y^{-1}$)	Gross efficiency (%)	Net efficiency (%)
South Lake	219	45	31	2.0	1.4
Temple Lake	561	31	13	0.5	0.2
East Lake	589	26	22	0.4	0.4
Ink Lake	712	91	77	1.3	1.1
Yu's Lake	1,013	194	166	1.9	1.6
Tea Leaf Bay	1,246	263	245	2.1	2.0
Inlet Bay	1,916	446	429	2.3	2.2

Table 28: Conversion efficiencies of ΣPP to annual fish yield (Fy), for water bodies of different productivities. Conversion efficiencies for lakes and reservoirs with ΣPP ⩽ 2500 g C $m^{-2}y^{-1}$ have been derived from Fig. 25, whilst for those with ΣPP > 2500 g C $m^{-2}y^{-1}$, yields have been assumed to lie on the upper portion of the logistic curve described by Liang et al (1981).

ΣPP (g C $m^{-2}y^{-1}$)	% conversion to fish yield
<1000	1 - 1.2
1000-1500	1.2 - 1.5
1500-2000	1.5 - 2.1
2000-2500	2.1 - 3.2
2500-3000	3.2 - 2.1
3000-3500	2.1 - 1.5
3500-4000	1.5 - 1.2
4000-4500	1.2 - 1.0
>4500	∿1.0

Table 29: Feeding practices of 70 cage operators at Lakes Buhi and Bato, Camarines Sur, Philippines (after Escover and Claveria, 1984, in press)

A Type of feed	Lake Buhi	Lake Bato
Rice bran	23	9
Rice bran and dried shrimp	14	2
Rice bran and "irin-irin"	7	-
Rice bran and coconut meat refuse	4	1
Rice bran, corn and "irin irin"	1	1
No feeding	1	7
	50	20
B Method of feeding		
Broadcast (dry feed)	32	7
Broadcast (wet feed)	12	6
Broadcast combination wet and dry	5	-
Do not feed	1	7
	50	20
C Frequency of feeding		
Once per day	12	-
Twice per day	14	2
Thrice per day	1	-
Once per week	4	2
Twice/Thrice per week	15	6
Four-Ten times per week	3	1
Once/Twice per month	-	2
	49	13

Table 30: Total-P content and P loadings[1] of various feedstuffs commonly used as supplementary feeds in semi-intensive tilapia culture. FCR values refer to O. mossambicus. Data from Jackson et al (1982), NRC (1977), and Balarin and Hatton (1979).

Feedstuff	total-P content (%)	FCR	total-P loading (k tonne^{-1} fish culture)
Rice bran	0.41	-	-
Copra meal	0.60	-	-
Brewery waste	0.53	12.60	63.38
Soya meal	0.67	3.04	16.97
Groundnut meal	0.64	4.91	28.02
Cottonseed meal	1.01	2.69	23.77

[1] P loadings calculated as:- total-P fed per tonne fish - total-P content per tonne fish harvested

Table 31: Summary of problem areas associated with the predictive models discussed in the text

Method of Culture	Problem	Solution
(a) Intensive Culture	Setting of desirable/ acceptable water quality criteria	- Research into the relationship between mortality of farmed fish, and envirinmental conditions in cages. - Research into the feedback effects of qualitative changes in the plankton community on cultured fish - Study of the economics of risk at high production sites
	Estimation of waste production	- Research into the nature and bioavailability of wastes, with particular emphasis on diet formulation and manufacture, and the influence of temperature and fish size on feed utilisation and waste composition - Research into the effects of harvesting schedule (continuous/quantum cropping) on waste output
	Estimate of impact	- Research into impacts in different types of inland water body (deep/shallow, N-limited/P-limited, oligotrophic/eutrophic/dystrophic, tropical/temperate, etc.)
(b) Extensive Culture	Estimates of conversion efficiencies	- Studies on predation efficiencies of planktivorous species under varying conditions (temperature, turbidity, different algal and zooplankton species, etc.) - Research into the effects of increased predation on one particular trophic level - Research into the effects of stocking density on predation efficiency and food utilisation - Research into poly- versus monoculture in enclosures - Research into diet of cultured species in pens and cages - Research into the design and siting of enclosures
(c) Semi-intensive culture	The relationships between supplementary feed quantity and quality, and fish production	- Research into the utilisation and nutritional role of materials used as supplementary feeds in pens and cages - Studies on the effects of stocking density on diet

Table 32: Production of O. niloticus in cages and pens, without supplementary feeding*, in Cardona, Laguna de Bay, Philippines, 1982-83. Cages are 3-5m deep.

Method of culture	Area (m^2)	Stocking density (fish m^{-2})	Stocking period (months)	Size at harvest (g)	Production (g m^{-2} $month^{-1}$)	Reference
Cage	138-2900	7.4	6.3	119	140	Lazaga & Roa, 1983
Pen	15000	20	4-6	170-250	833-850	Guerrero, 1983

* In fact, limited amounts of feed were given to the caged fish

Table 33: Estimated potential for reduction in total-P wastes associated with intensive fish culture through various feed manufacturing and management options. Costs estimated as ranging from * (inexpensive) to *** expensive.

Option	Method	Cost	Reduction
Reduction of dust added to water body	- Improved manufacturing (e.g. use of steam conditioning, increased mash transit time in steam conditioner, etc[1])	**	2%+
	- Sieving of feeds by farm staff prior to use	*	
Reduction of pellet losses to the environment	- Improved feeder design	**	
	- Careful siting of cages	*	
	- Careful adjustment of feeding regime to prevailing environmental conditions	*	10%+
Reduction of total-P load in wastes	- Reduced P content in feeds	**	30%+
	- Use of high digestibility diets	*	30%
Removal of surplus P added to lake or reservoir during culture	- Pumping and removal of wastes from under cages	***	?
	- Removal of mortalities to site on shore	*	10%[2]
	- Trapping and removal of escaped fish	*	1.5%[2]
	- Utilisation of wastes through combination with extensive culture	?	?

[1] see ADCP (1983)

[2] these figures depend very much on extent of mortalities and number of escaped fish

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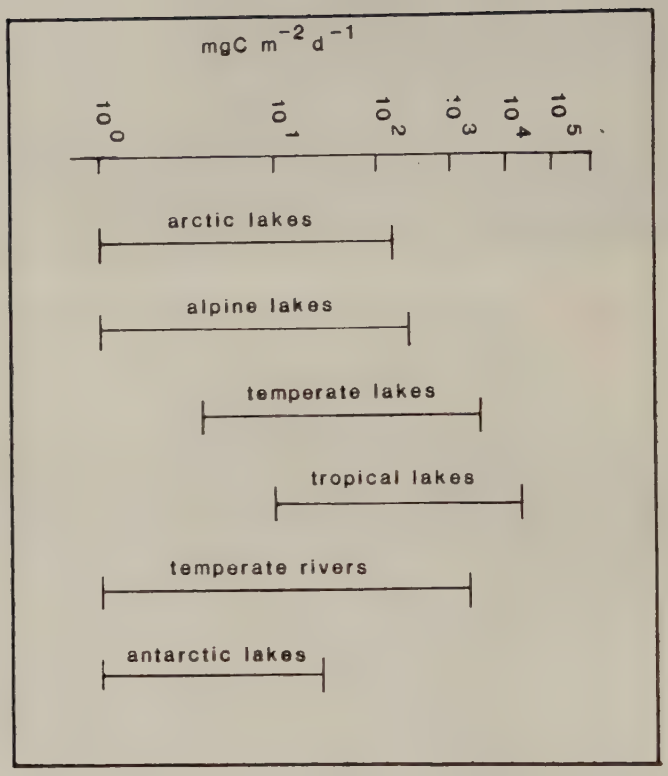

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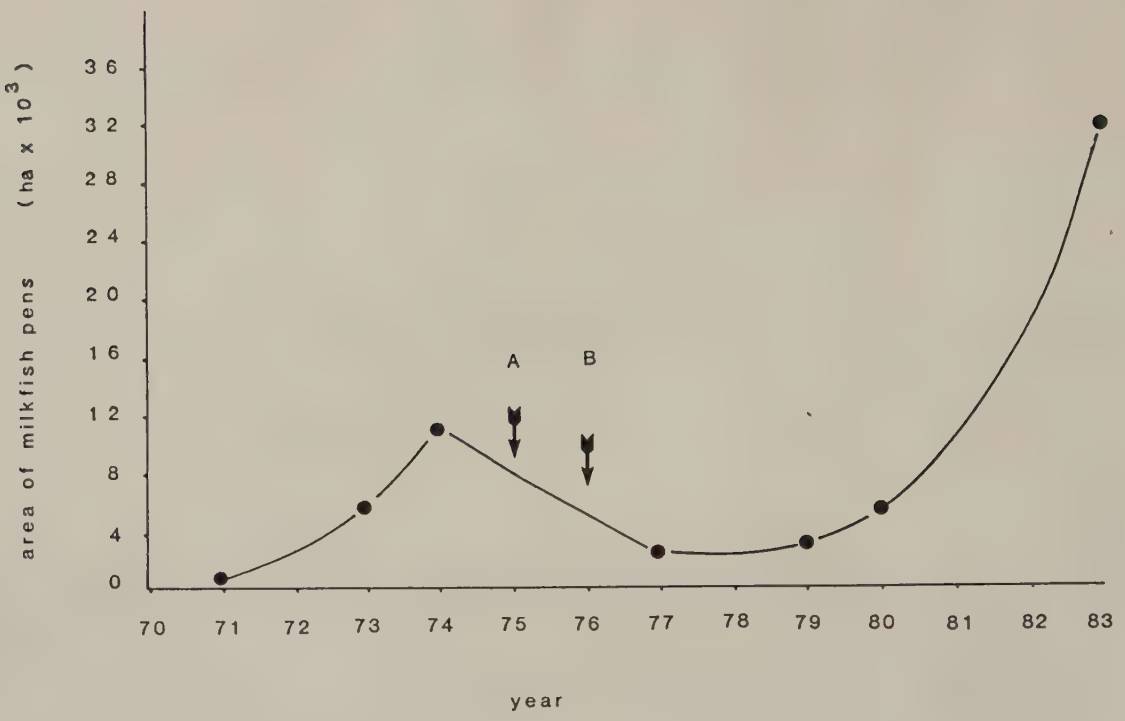

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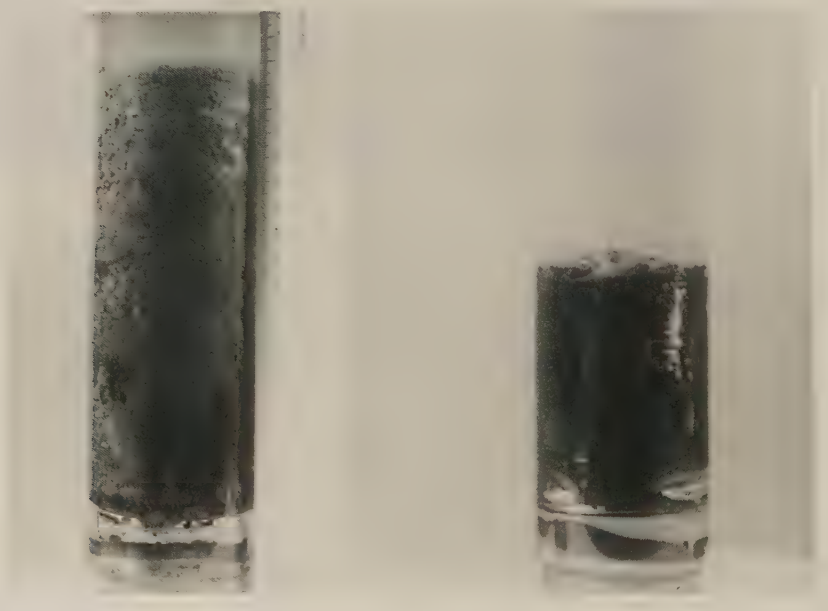

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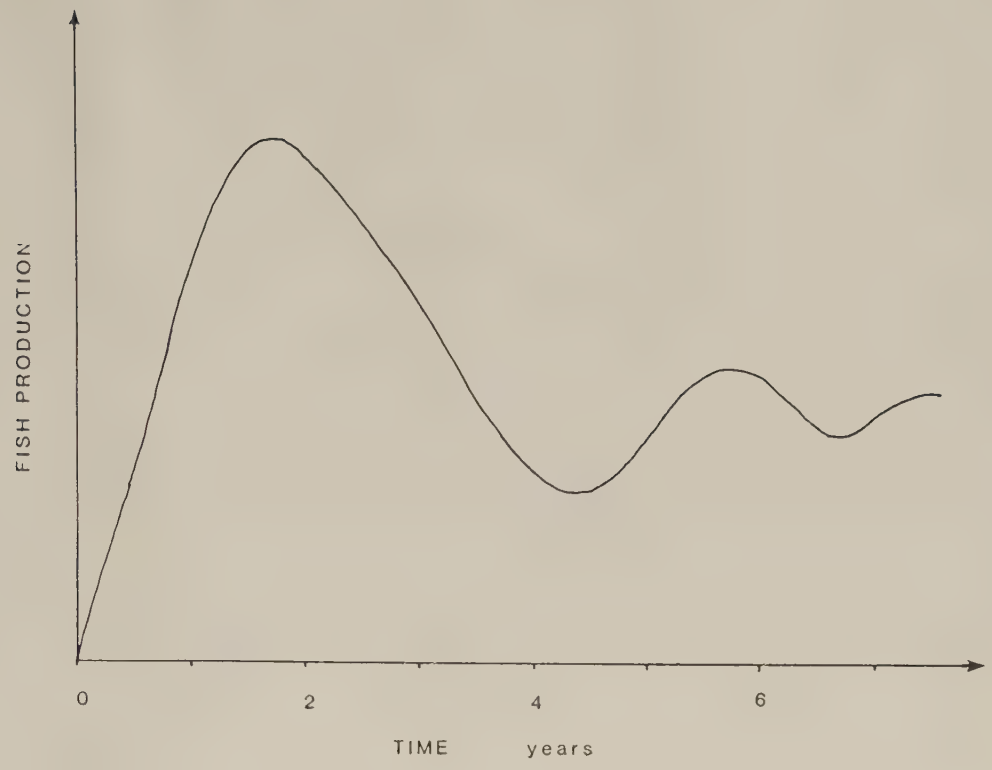

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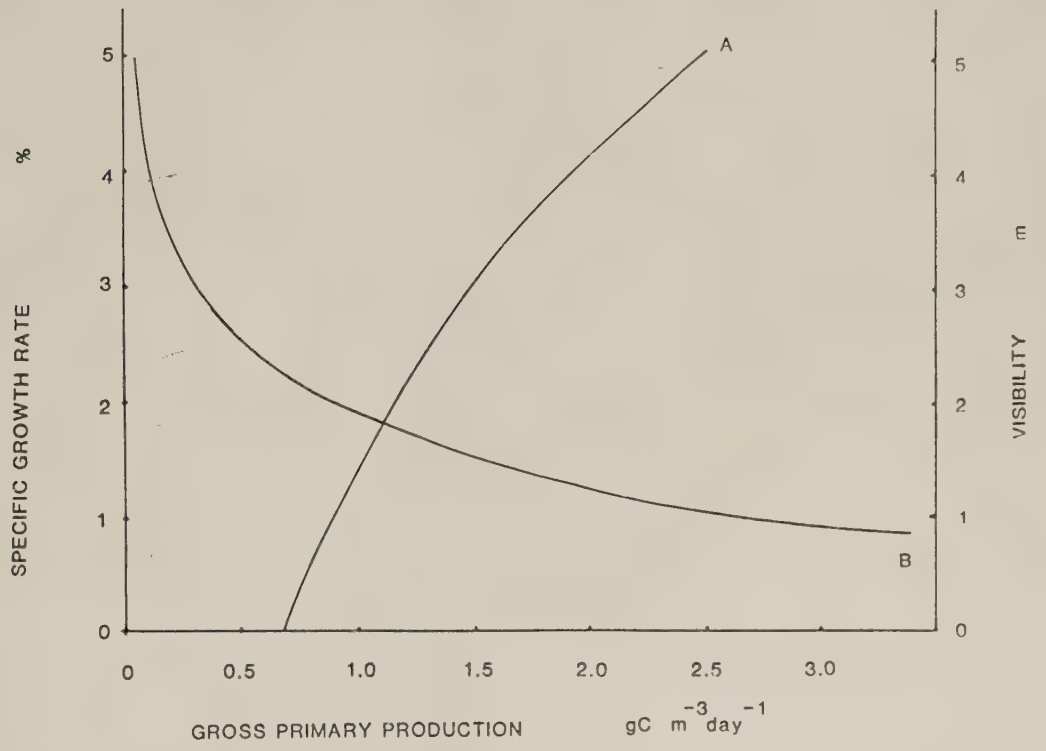

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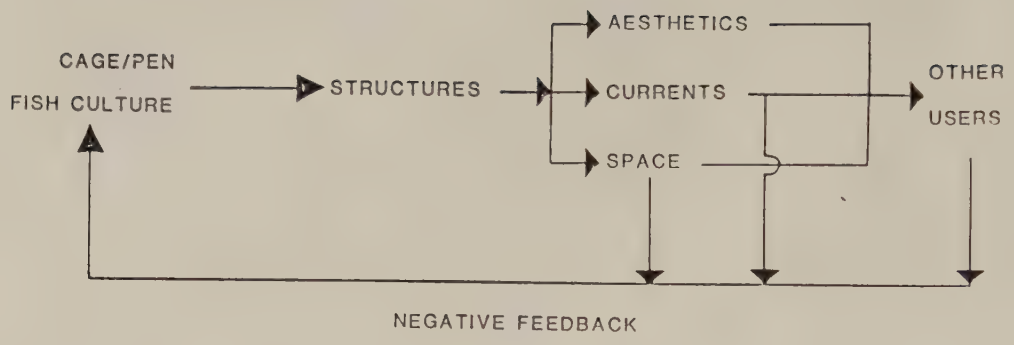

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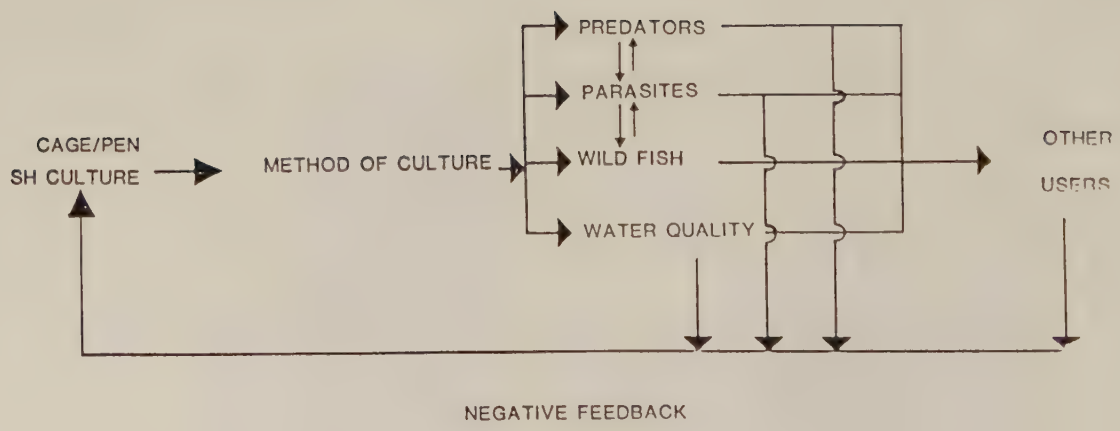
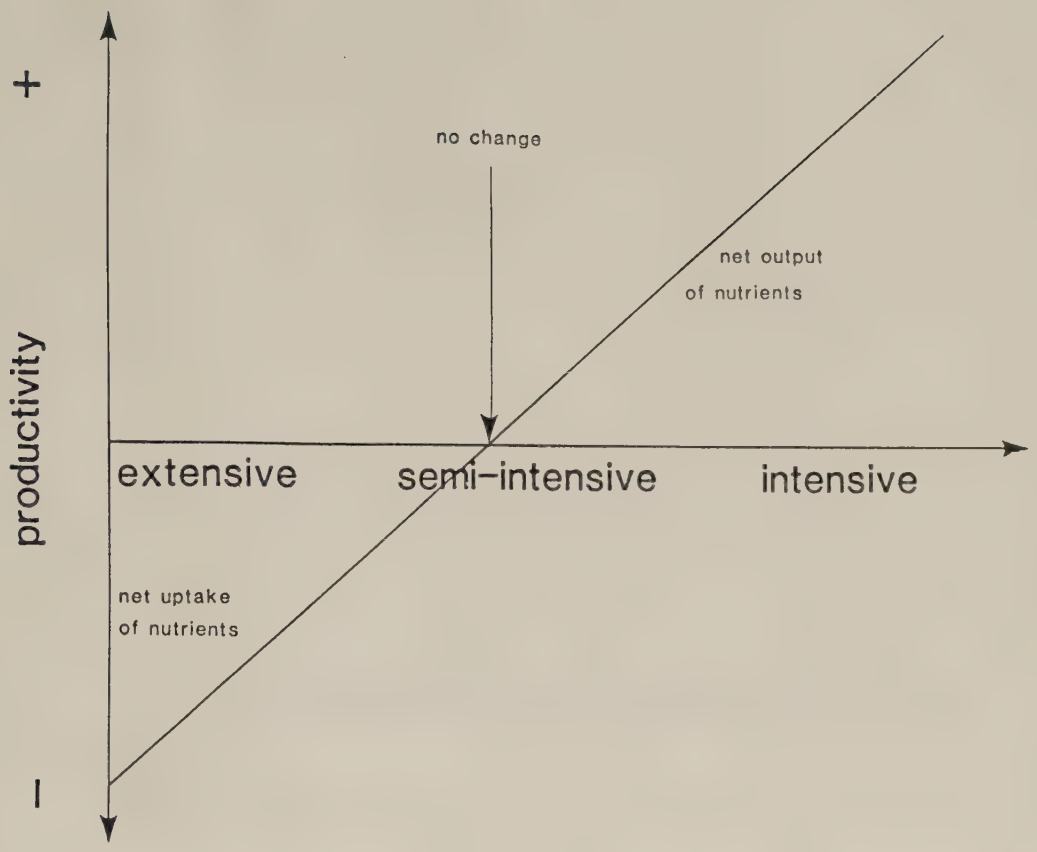


Fig. 13. The impacts of cage and pen culture methods on the environment



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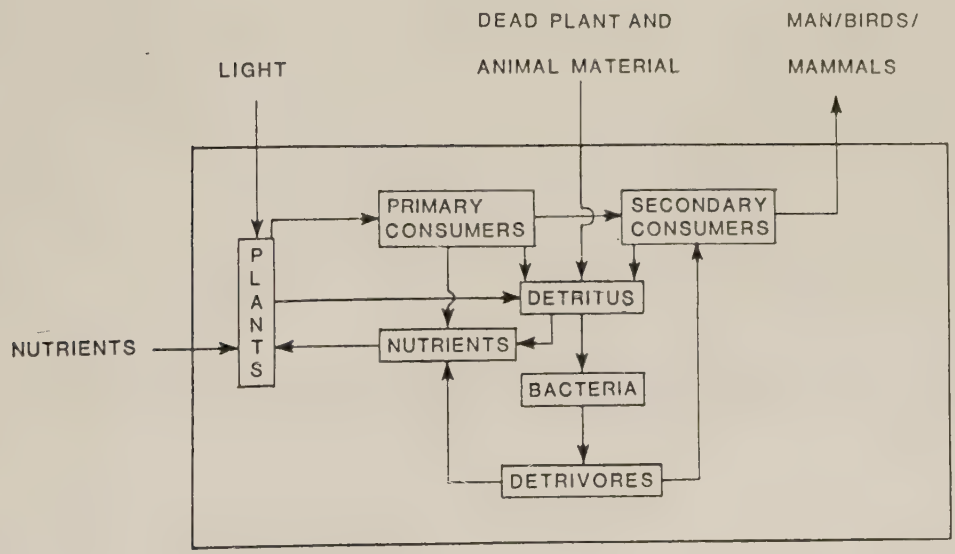

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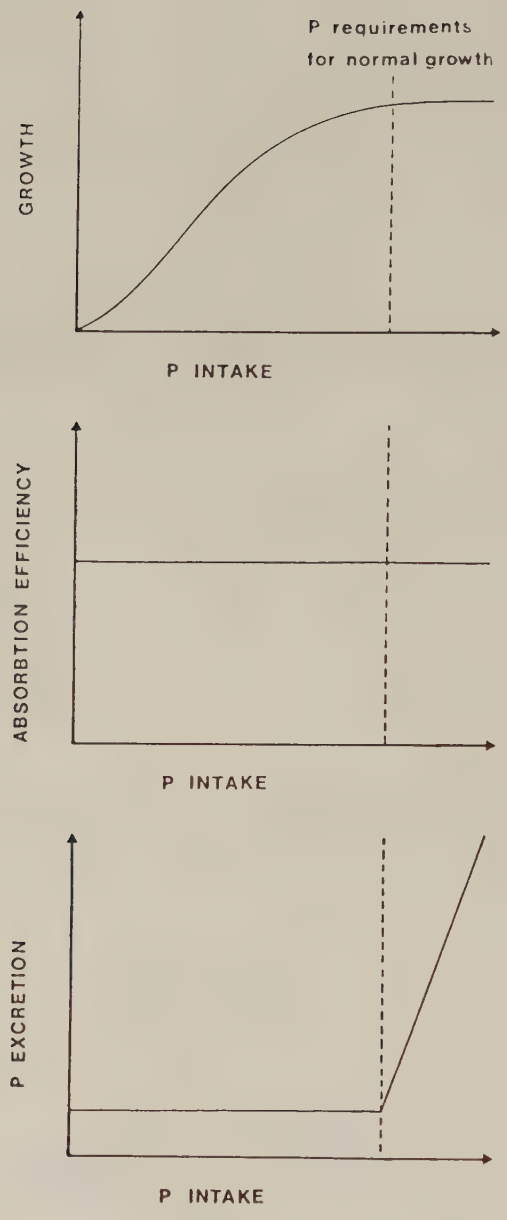

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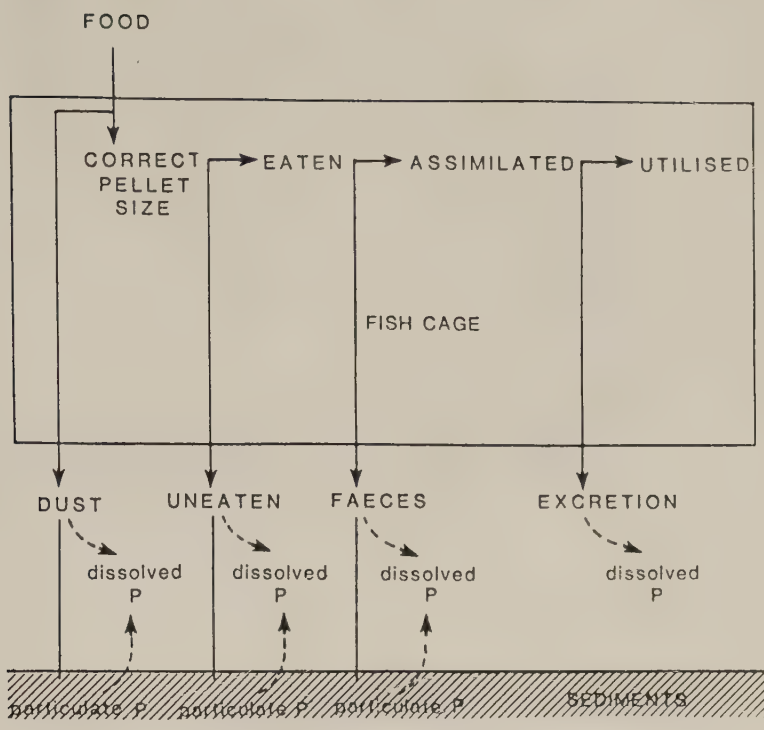

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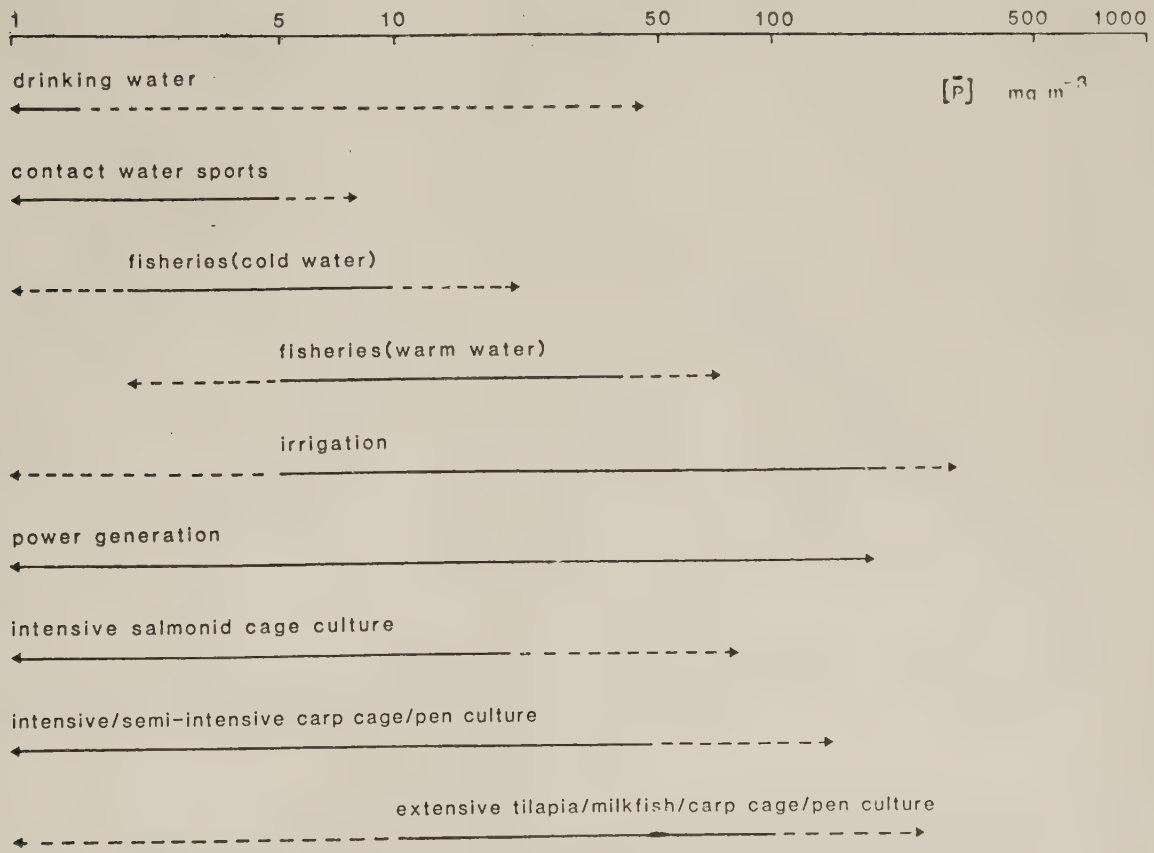

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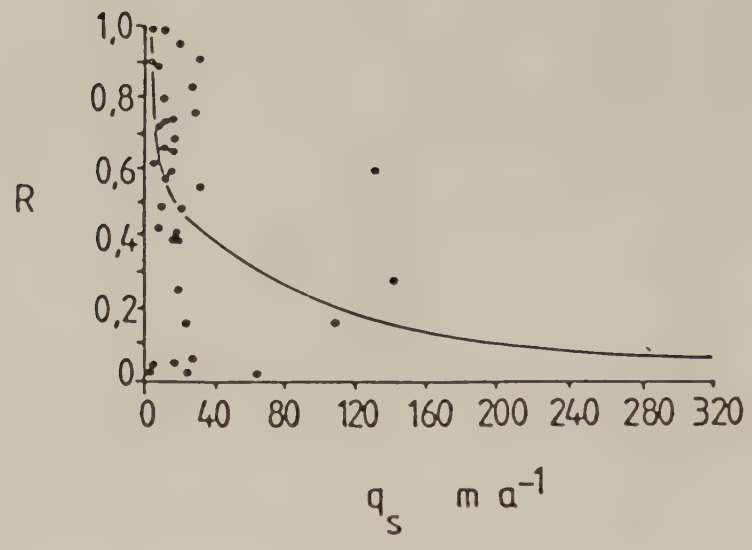

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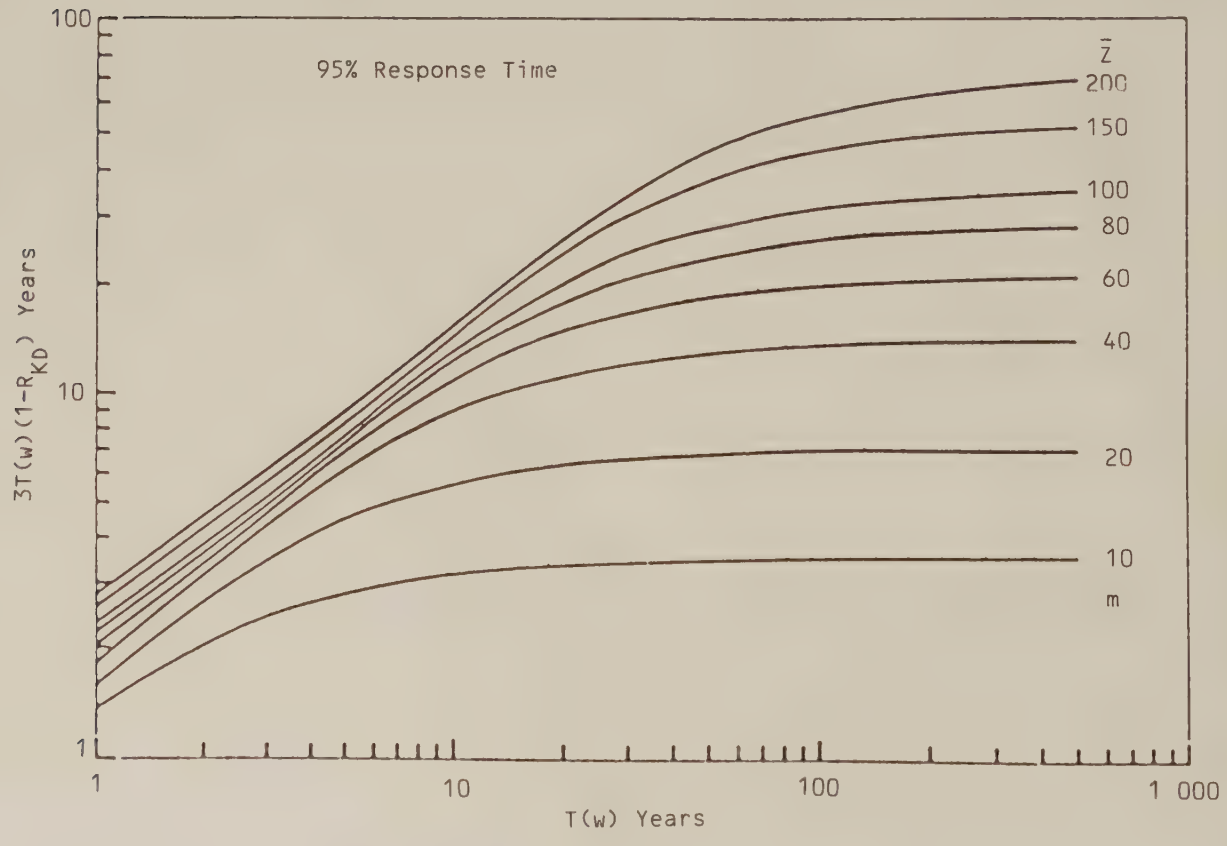

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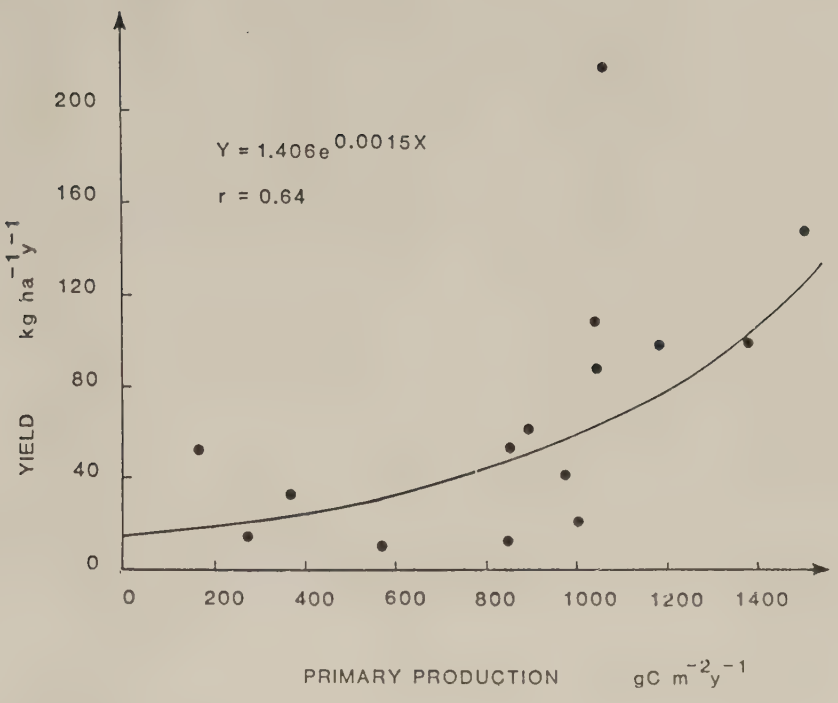

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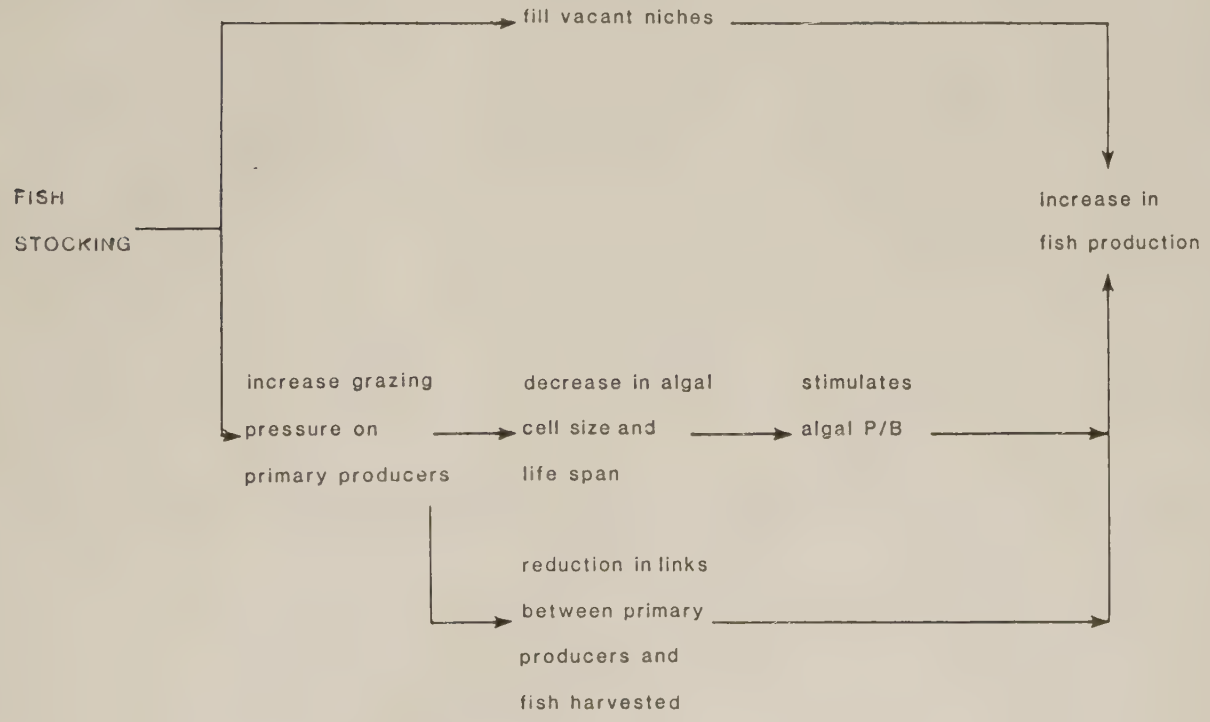
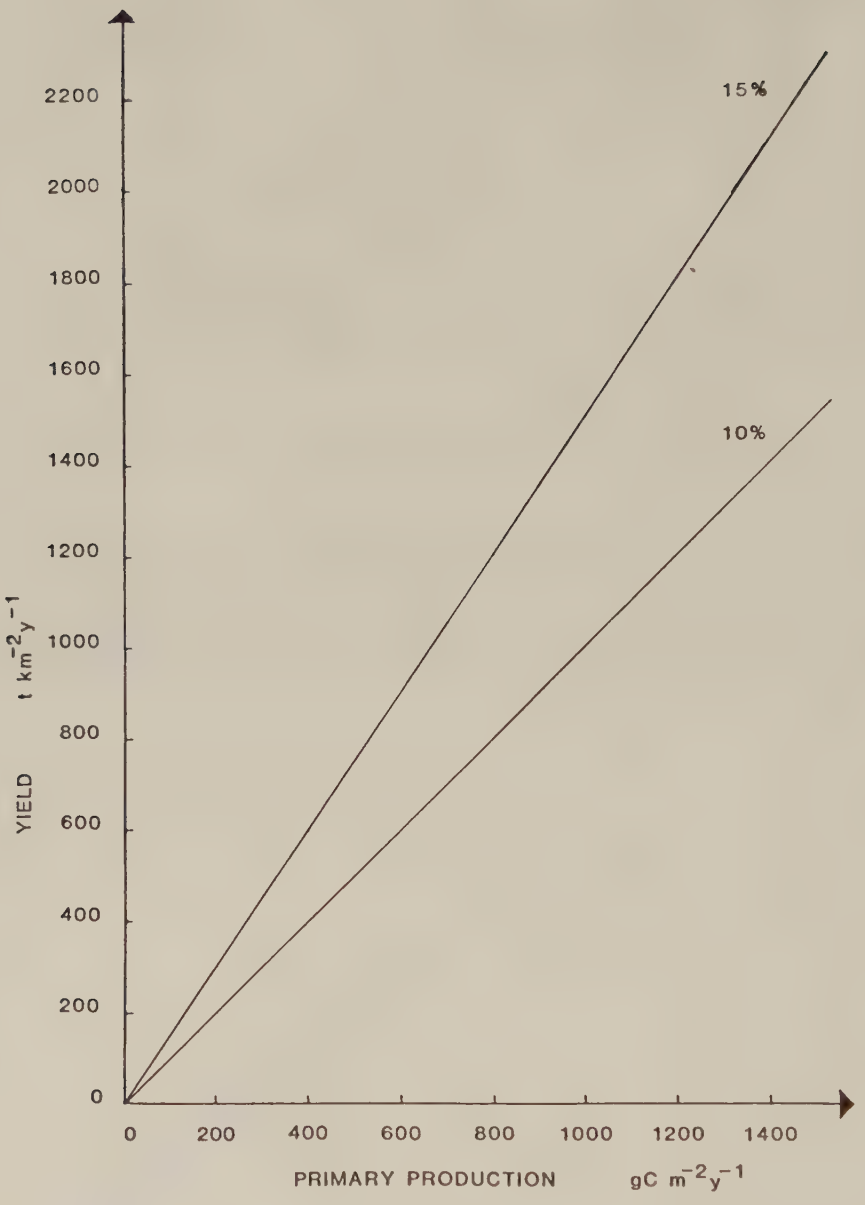

fill vacant niches
FISH STOCKING
increase in fish production
increase grazing pressure on primary producers
decrease in algal cell size and life span
stimulates algal P/B
reduction in links between primary producers and fish harvested

Fig. 22. Summary of reasons for stocking freshwater bodies with fishes which feed at the aquatic food web base (see text)



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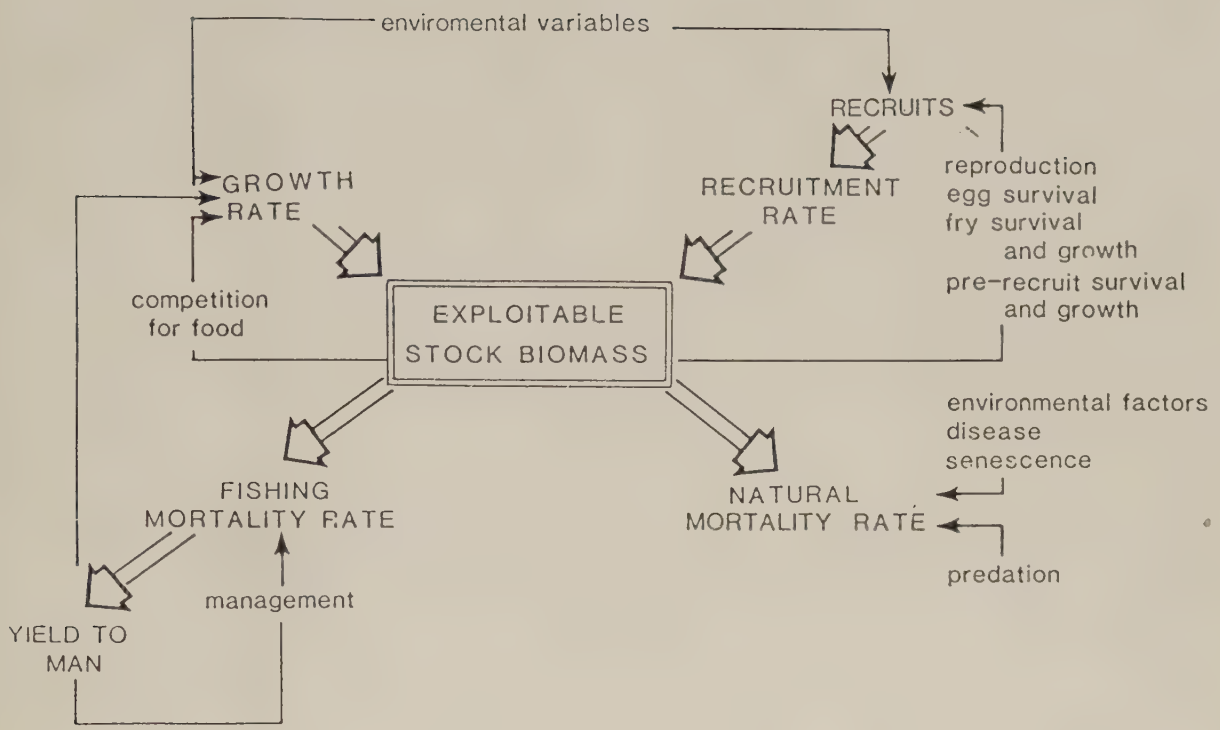

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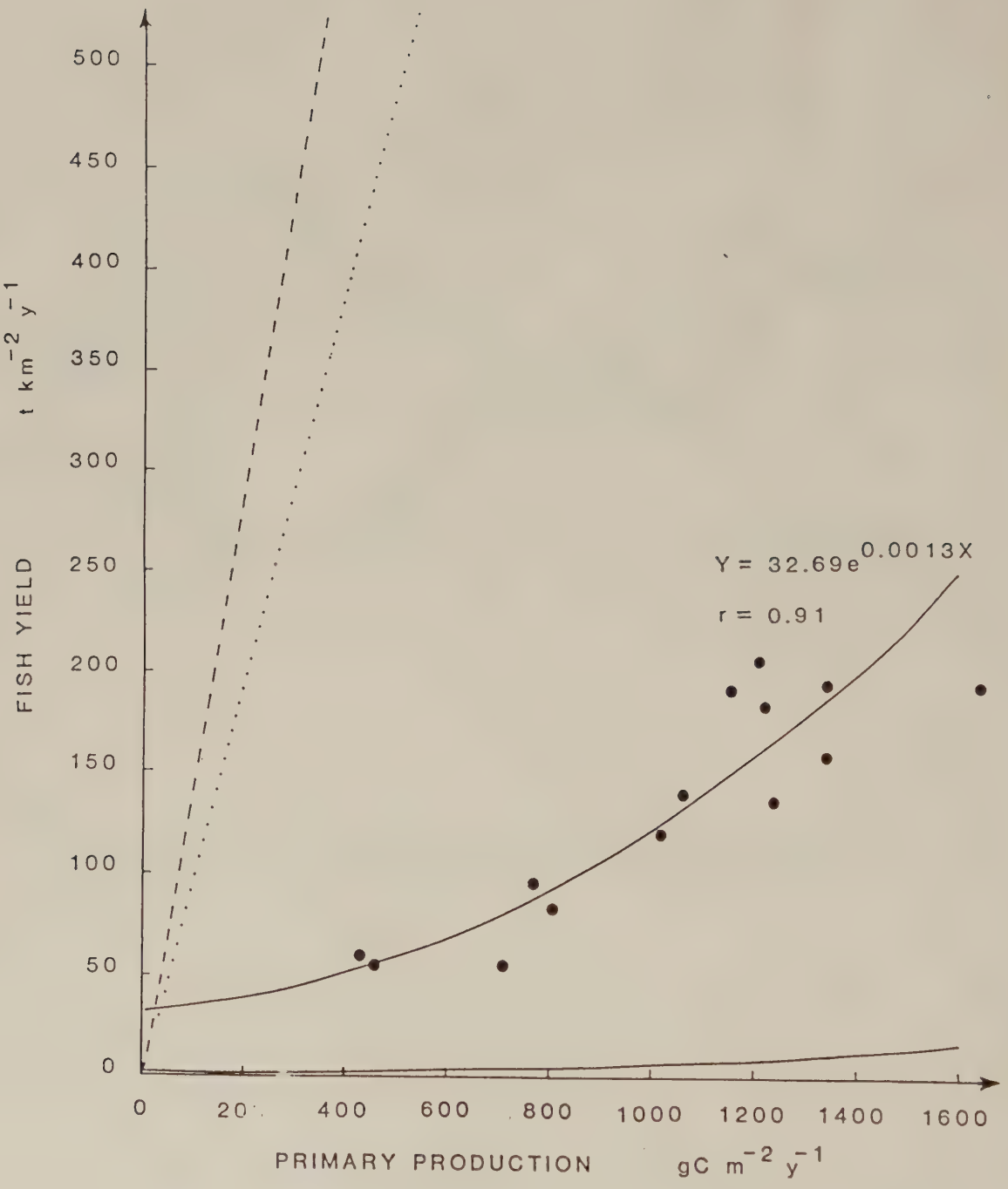

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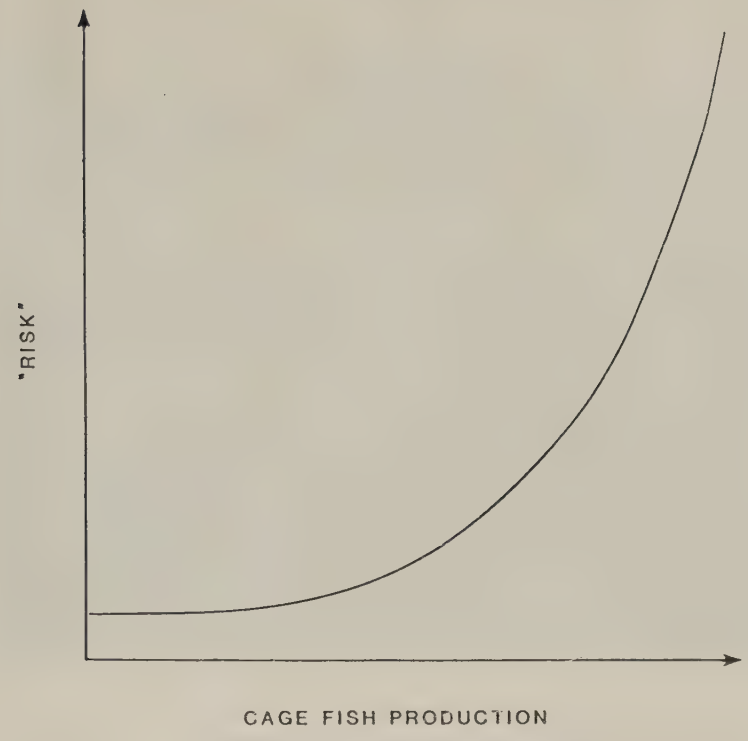

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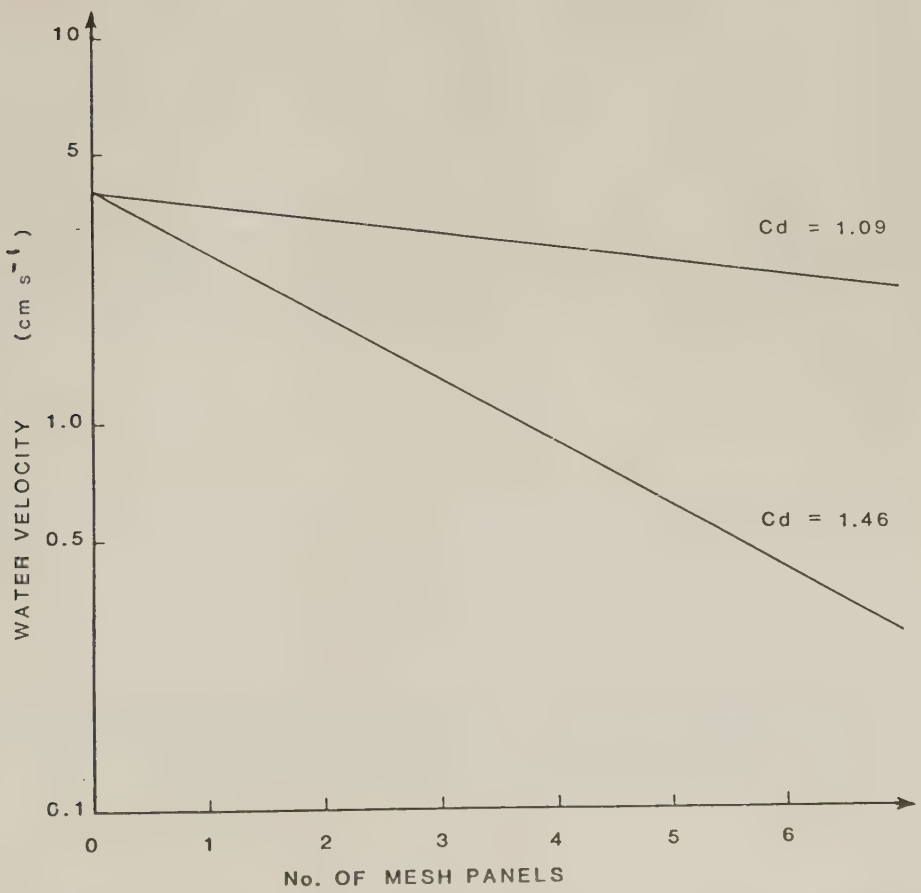

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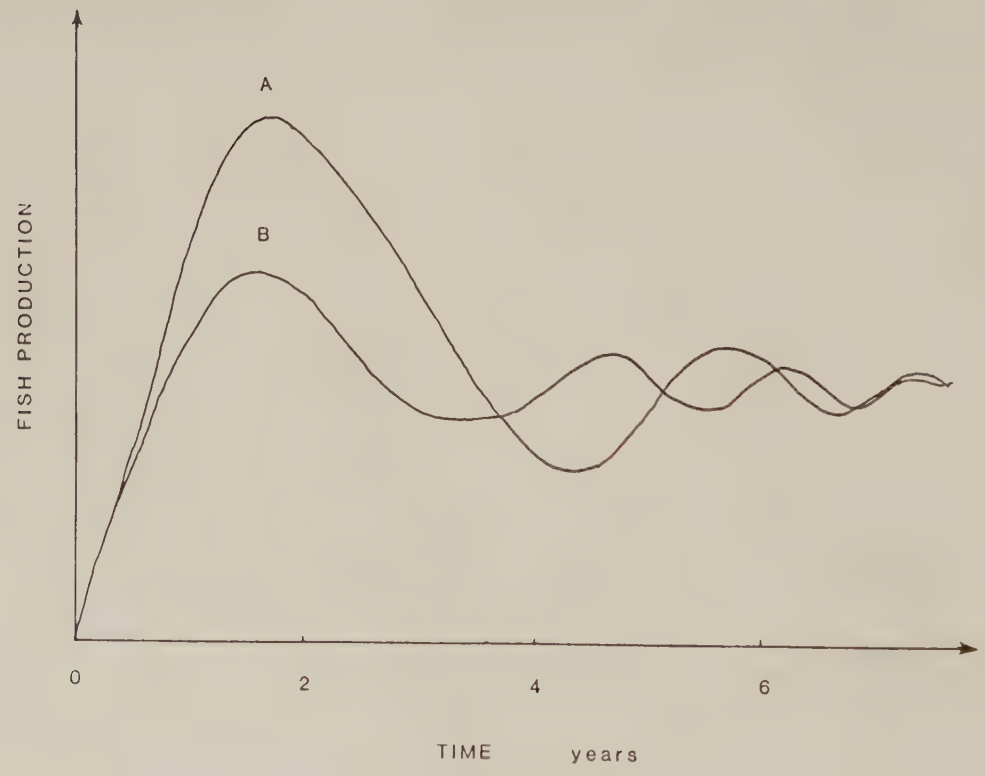

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Appendix 1

Example of intensive cage rainbow trout production assessment for a hypothetical natural lake in Europe (see Section 4.3.3.2).

Site:

Surface Area of Lake = 100ha (calculated from map).

Mean depth, $\bar{z}$, = 10m (from hydrographical survey).

Flushing coefficient, , = 1 yr^{-1} (determined from sampling outflows).

Method

Step 1: Determine $[P]_i$ of lake prior to development. 15 mg m^{-3} as determined from monitoring programme.

Step 2: Set maximum acceptable [P], $[P]_f$, following the introduction of fish culture. Assuming no other developments or criteria take precedence, then 60 mg m^{-3} is chosen as target $[P]_f$.

Step 3: Determine $\Delta[P]$

$$\Delta[P] = [P]_f - [P]_i = 45 \text{ mg } m^{-3}$$

$$\text{Since } [P] = \frac{L_{fish}(1-R_{fish})}{\bar{z}\rho}$$

$$L_{fish} = \frac{\Delta[P]\ \bar{z}\rho}{1-R_{fish}}$$

R_{fish} is taken to approximate R calculated from the equation of Larsen and Mercier (1976) (see Table 23)

$$R = \frac{1}{1 \quad 0.747\rho^{0.507}}$$

$$= 0.54$$

$$\therefore L_{fish} = \frac{45 \times 10 \times 1}{0.54} = 833 \text{ mg } m^{-2}\ y^{-1}$$

$$= 0.833 \text{ g } m^{-2}\ y^{-1}$$

Step 4: Since the lake has a surface area of 10^6 m^2, the total acceptable loading = 0.833×10^6 g y^{-1}

$\therefore$ the tonnage of fish that can be produced, assuming a P loading of 17.7 kg $tonne^{-1}$ (see Table 16)

$$= \frac{0.833 \times 10^6 g}{17700 g} = \underline{47 \text{ tonnes per annum}}$$

This value should be used as a pre-development guide to the carrying capacity of the lake. However a monitoring programme must be implemented, and actual production levels adjusted in the light of information collected on water quality - principally algal biomass and O_2 levels.

Appendix 2

Example of extensive cage tilapia production for a hypothetical tropical reservoir (see Section 4.4.5).

Site:

Surface Area = 100ha.

Method:

Step 1. Calculate the annual gross primary production, ΣPP. 1200 g C m^{-2} y^{-1}, as determined by regular measurement.

Step 2. Convert to annual fish yields, using Table 28.

i.e. ~ 1.3% ΣPP → fish
= 15.6 g fish C m^{-2} y^{-1}
= 156 g fish m^{-2} y^{-1}
= 156 tonnes annual fish production for whole lake.

Step 3. Assuming 2 crops per year, determine culture periods. ΣPPc1 ≡ ΣPPc2, in order for fish to reach target market size.

ΣPP (Nov. - May) = 570 g C m^{-2}
ΣPP (June - Oct.) = 630 g C m^{-2}

One seven month, and one five month cycle are chosen.

Assume 25g fish stocked

Assume 8 pcs. per kilo target market size (i.e. 125g each)

each fish grows 100g during culture period.

stocking requirements = 156 tonnes/100g = 1.56×10^6 fingerlings.

= 780×10^3 fingerlings per crop.

Appendix 3

Example of semi-intensive cage tilapia production assessment for a hypothetical tropical lake (see Section 4.5).

Site:

Surface area = 100 ha

mean depth, $\bar{z}$, = 10 m

flushing coefficient, ρ , = 1 yr^{-1}

Method:

Step 1. Calculate the annual gross primary production, ΣPP.1200g C m^{-2} y^{-1}, as determined by regular measurement.

Step 2. Convert to annual fish yields, using Table 28.

i.e. 1.3% ΣPP → fish

= 156 tonnes annual fish production for whole lake.

Step 3. Assume 100 tonnes of cottonseed meal and 20 tonnes of soya meal is available for feed each year. Using FCR values from Table 30:-

6.6 tonnes can be grown from soya meal and
37.2 tonnes can be grown from cottonseed meal.

Step 4. Total P loadings from fish grown on supplementary food (from Table 30):-

(6.6 x 16.97) + (37.2 x 23.77) = 996.24 kg.

The resultant increase in [P] can be calculated from Dillon and Rigler's (1974) formulation: -

$[P] = \frac{L(1-R)}{\bar{z}\rho}$, where L is the areal loading from the fish cages; (996.24 kg/10^6 m^2 = 996.24 mg m^{-2}); R is derived from Larsen and Mercier (1976) (Table 23) (1/1 + $0.747\rho^{0.507}$ = 0.54):-

$$[P] = \frac{996.24\ (1 - 0.54)}{10 \times 1} = 45.82 \text{ mg } m^{-3}$$

Using the formula: -

$\Sigma PP_{fish} = 31.1\ [\overline{P}]^{0.54}$ (OECD, 1982) to relate increase in [P] to primary production,

$\Sigma PP_{fish} = 31.1 \times 45.8^{0.54} = 50.5$ g C m^{-2} y^{-1} increase.

Step 5. Fish yields due to ΣPP_{fish} can be calculated using the conversion efficiencies in Table 27: -

$\Sigma PP_{fish} \rightarrow$ fish = 0.5g fish Cm^{-2} y^{-1}

= 5g fish m^{-2} y^{-1}

= 5 tonnes fish production for whole lake.

ΣFy, the total fish yield can now be calculated: -

$\Sigma Fy = (0.073 \times 1200 \times 10) + [(100/2.69) + (20/3.04)] + (0.01 \times 50.5 \times 10)$

= 205 tonnes fish $annum^{-1}$

Appendix 4

Calculations of appropriate fish stocking densities for extensive cage culture.

The following stocking density models assume that the growth rate of extensively cultured fishes, such as tilapias, is limited either by food supply or by O_2.

Model A Food Supply

If the current velocity through the cage is determined, and the filtering capacity of the fish known, then we can calculate the maximum permissable stocking density SD_{MAX}, as governed by food supply:-

$$SD_{MAX} = \frac{V_i \times 1000}{F \times L}, \quad \text{where } SD_{MAX} = \text{fish } m^{-3};$$

V_i = velocity of water inside the cage (m s^{-1}); F = filtering ability of fish (l s^{-1}); and L = length of cage parallel to the prevailing current.

V_i, L and A can be determined by direct measurement, whilst F can be derived from published data on buccal cavity size, and gill opercular beating rates (see Hoar and Randall, 1976). The following calculations are based on typical values: -

Cage size = 5 x 5 x 4m (100 m^3)

L = 5m

V_i = 0.1 cm s^{-1} (0.001 m s^{-1})

F = 30 ml s^{-1} $fish^{-1}$ (data for 18 cm+ *S. aureus* and *S. galilaeus*. Drenner *et al*, 1983).

$$SD_{MAX} = \frac{0.1 \times 1000}{0.3 \times 5} = 667 \text{ fish } m^{-3}$$

This is very much higher than the typical stocking values of 5 - 50 fish m^{-3} for extensive cage culture. However, the model assumes that the fish themselves do not contribute to the drag forces exerted on currents flowing through cages, or that conversely the movement of fishes in the cages may increase circulation. The relative importance of these two factors remains unknown. Also, it is assumed that the fish fully evacuates its buccal cavity on each occasion, which is unlikely.

Model B O_2 requirements

If the current velocity through the cages is computed, and the O_2 concentration of the water known, then the supply of O_2 to the fish cage can be calculated. If the O_2 requirements of the caged fish are computed, assuming worst possible conditions (high temperatures, small fish, requirements following a meal), then we can calculate the appropriate stocking density: -

Cage size = 5 x 5 x 4m

$\therefore$ A = 20 m^2

L = 5m

V_i = 0.001 m s^{-1}

Temp. = 30°C

$\therefore$ O_2 content of water, assuming 100% saturation at sea level = 7.6 mg l^{-1}

$\therefore$ O_2 supply to cage = V_i x A x 1000 x 7.6 = 152 mg O_2 s^{-1}

= 5.47×10^5 mg O_2 h^{-1}

Assume O_2 content of water leaving cage = 3 mg l^{-1}

Total O_2 leaving cage each hour = V_i x A x 1000 x 3600 x 3

= 2.16×10^5 mg O_2 h^{-1}

O_2 available to fish = 3.31×10^5 mg O_2 h^{-1}

Assuming cages stocked with 50g tilapia, O_2 requirements following a meal (2% body weight per day) = 328 mg O_2 kg^{-1} h^{-1})data from Ross and Ross, 1983; L.G. Ross, unpublished data).

$\therefore$ Sustainable biomass of fish in cage = $\frac{3.31 \times 10^5}{328}$ = 1009 kg

$\therefore$ Stocking density = 10.1 kg m^{-3}

This value is similar to that typically used in extensive cage culture.

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ISBN 92-5-102163-5